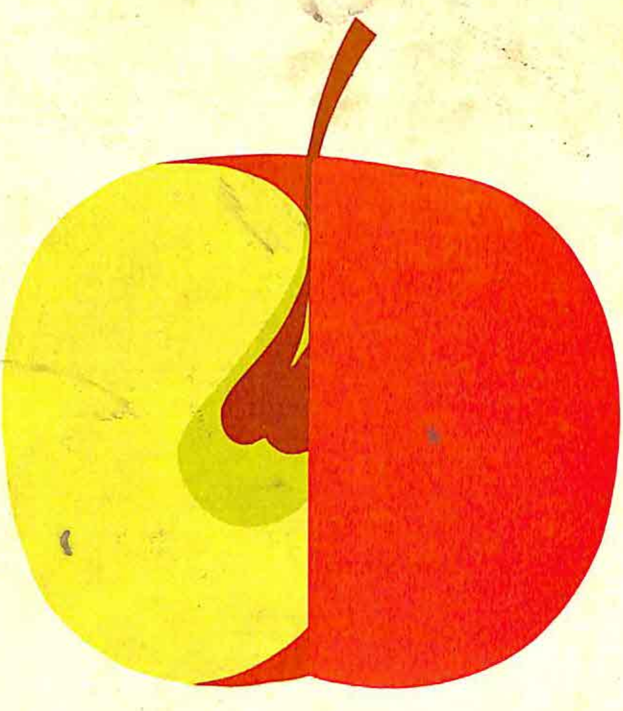

Teaching Children Science: an Inquiry Approach

Kuslan & Stone

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STATE INSTITUTE OF EDUCATION * Govt. of West Bengal

Teaching Children Science: an Inquiry Approach

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For Our Wives, Dorothy and Eileen

The major purpose of this book is to introduce preservice and in-service elementary school teachers to the joy and the labor of teaching science by Inquiry. Modern science instruction is far different from the traditional book-centered science curriculum formerly imposed on children. The new currents in science teaching stress the importance of deriving learning from direct experiences with scientific phenomena. This approach, modeled after the investigative processes of scientists, is called the Inquiry or discovery approach. It is a strategy for learning that we believe is particularly appropriate from both a psychological and a scientific point of view.

Educators now know much more than ever before about how children learn and how this learning can be directed so that it is both willing and effective. We believe that elementary science teaching which meets the demands of our complex, science-oriented society is impossible unless teachers are aware that the roots of science teaching are deeper than mere teaching methodology or knowledge of the facts of science. For this reason, the purpose of the first chapter is to present a different picture of science than the one presented in the usual college course in physics, chemistry, or biology. This chapter is a description of the "tactics and strategy" of science and proposes a model of the scientific endeavor in terms of its characteristics and processes. The second chapter deals with those phases of educational psychology that condition science learning much more comprehensively than do most methods textbooks on elementary science. This chapter will provide the reader with the operational foundation

Preface

for the teaching of science and will help him understand the conditions that hinder or enhance learning.

With this basis, the evolution of elementary science teaching, which is the subject of Chapter 3, becomes more pertinent to the contemporary educational scene. The fourth, fifth, and sixth chapters present a philosophy, rationale, and interpretation of Inquiry teaching, including a comprehensive review of the "new" curricula in elementary science. The remainder of the book describes the different kinds of educational experiences (experiments, field trips, motion pictures, trade books, and evaluative activities) that provide the classroom teacher with the necessary tools for Inquiry teaching.

Each chapter is followed by a summary of the important points made in the chapter and by questions designed to stimulate the student to think critically about the problems and suggestions that have been made.

Most of the firsthand experiences of Chapter 12, Laboratory Experiments, are planned for a course in the teaching of elementary science, not for use in the elementary school. They are written to involve teachers in a kind of science experience that they have not often encountered in conventional science courses—an introduction, on their level, to scientific investigation, so that they may better understand the problems and thought patterns that their own classes will encounter.

We wish to thank the many colleagues, researchers, and students who have assisted us with this book. Although we cannot name them all, we do wish to acknowledge the special help of Dr. Herbert Thier, Dr. John Mayor, Dr. J. Myron Atkins, and Dr. A. L. Braswell. And we particularly wish to thank Mrs. Ruth DiLeone, who spent countless hours typing and retyping the many versions with which we showered her, and Carol Agee, who rescued us from many syntactical and typographical errors.

Louis I. Kuslan
A. Harris Stone

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Teaching Children Science: an Inquiry Approach

1

The nature of science

Science is more than the detailed organization of minute facts and complicated theories which laymen so often believe it to be. The misconception that science *is* facts and theories arises from the kind of education which laymen have received. The textbooks which they studied in high school and college are partly responsible, because textbooks have often been crammed with scientific information. They are the structured end-products of science, a distillation of the labors of generations of scientists who have devoted their lives to "The Search for Truth."

But textbooks are tools. Of themselves, they are not necessarily narrow or limiting. Instruction in the sciences is many-faceted, and the skilled teacher who organizes the facts of science into a meaningful, integrated body of knowledge inevitably enlarges the beginning student's understanding of science and of the place of science in modern society.

Unfortunately, traditional high school and college science instruction emphasizes information and classification of information. It is therefore natural for the student to conceive of "the scientific endeavor" as *his* personal struggle to memorize, perhaps eventually to understand, the facts and principles of the sciences. He emerges from his brief exposure to chemistry, physics, or biology with a painfully acquired store of knowledge, but without understanding why men devote entire lives to science or how the facts and principles which he studied were wrenched from a stubborn and resisting nature.

This argument, of course, is not intended to minimize the importance of factual information – the change in length of a steel rod with temperature, for example, or the solubility of nitrates in water. Science is built on a foundation of facts and must always seek new facts, but instruction in science for the non-scientist must also strive for goals far nobler than mere recall of facts and understanding of scientific phenomena.

Defining science

Science is not easily defined, and for this reason it has many definitions. Whatever science is, its identification as "organized knowledge" illuminates only one of its elements. The telephone directory is a well-organized collection of facts; but no one pretends that this useful volume is a scientific treatise. The collected knowledge which is the "product" of science has a dynamic counterpart, the "process" of science. Science is simultaneously a *kind* of knowledge and a *way* of gaining and using that knowledge. Texbook science tends to be only product. Real science is *both* product and process, inseparably joined.

This is clearly what James B. Conant, the eminent scientist and educator, had in mind when he described science as "an inter-connected series of concepts and conceptual schemes that have developed as a result of experimentation and observation, and are fruitful of further experimentation and observation."[1] Facts emerge from painstaking observation and skilled experimentation. These facts suggest certain concepts and generalizations which, in turn, direct new observations and experiments by which their validity is ultimately tested.

If, as a first approximation, a concept is identified as an abstraction or principle which is derived from experimental or observational fact, then Conant's "conceptual scheme" is "*a working hypothesis on a grand scale.*"[2] An example of a conceptual scheme or comprehensive theoretical treatment of this kind is the statement that "we live in an ocean of air." Here, in a few words, is summarized the accumulated experience of three centuries of scientific research on air pressure, vacuum, wind currents, gas density, and temperature. It is a fact of nature, firmly founded on experiment and observation, that under the proper conditions a column of mercury will stand thirty inches high in a tube. This and related facts lead to the concept (an abstraction from experience) that the atmosphere exerts pressure. The terms "air" and "pressure" are concepts in their own right, and from these and associated concepts, the conceptual scheme "we live in an ocean of air" is built.

Unless the conceptual scheme leads to new ideas, to new thoughts and new knowledge, it is of little value to the scientist. If further investigation is not stimulated, the conceptual scheme is barren and worthless.

If man inhabits an "ocean of air," it should be possible to explore this ocean, to chart its currents, and to investigate its phenomena in much the same way that such fluids as water are studied.

Science and power

Man's mastery of nature, imperfect though it is, did not arise out of the magical incantations of primitive medicine men, but out of man's endeavor to understand the order of nature. Power over nature has come from this understanding, and, therefore, understanding which leads to higher and more embracing levels of ordered knowledge is one goal of the scientist. In its way, magic was an attempt to understand and manipulate the order of nature, but because magic was subjective and animistic, it was irrelevant to the world and failed to give man the control he sought.

Because man gains power to reshape his world in proportion to his insight into that world, science is relevant to society in a new and crucial way. For example, the social, political, and economic problems associated with nuclear energy, automation, and jet-age mobility illustrate dramatically the impact of applying scientific expertise to everyday existence. The difficulty of adjusting to change is an ancient problem, but the rate of change is infinitely greater today than ever before. It seems almost inconceivable that only a few decades ago science was regarded by practical men as of little consequence. Dr. Conant once illustrated their attitude by an amusing anecdote:[3]

> At the time of our entry into World War I, a representative of the American Chemical Society called on the Secretary of War, Newton Baker, and offered the service of the chemists in the conflict. He was thanked and asked to come back the next day. On so doing, he was told by the Secretary of War that while he appreciated the offer of the chemists, he found that it was unnecessary as he had looked into the matter and found the War Department already had *a* chemist.

In 1939, the year in which Professors Hahn and Strassmann discovered the fission of uranium nuclei, the United States government spent about fifty million dollars for scientific research. Today the government spends billions of dollars each year on research and on the application of that research. One single piece of apparatus under construction at Stanford University will cost well over $100,000,000 and will require more than $20,000,000 to operate each year. Only a national government can afford to pour such sums into scientific research.[4]

Science and the technology with which science is associated are inextricably interwoven into the very fabric of modern society; and this intimacy is responsible for many of the problems which face citizens today who are "dis-educated" in science. They have been taught at—exposed, as it were, to science teaching—but exposure is not education. Citizens who do not understand the nature of science are not in a position to evaluate its aims and aspirations. This kind of understanding comes from firsthand investigation of a scientific problem in the course of which the tactics and strategies of the scientist are discovered. How can scientists expect the layman to appreciate the contributions of the sciences without some kind of direct participation in the scientific endeavor?

The content of science changes in a rapid, almost frightening manner. It has been estimated that the lifetime of a hypothesis in small-particle physics, a branch of nuclear physics, is only four years. The scientifically literate layman therefore must face continual frustration in an age in which it is literally impossible for even the specialist to be aware of the implications of the continual flow of new knowledge in his own narrow field. The fantastic proliferation of science is hinted at in the number of scientists and scientific publications, which doubles approximately every ten years.

This paradox is very real. The layman should know a great deal about this dynamic force which affects his very existence. Yet, is it reasonable to expect him to master physics, chemistry, astronomy, biology, and geology? It is clear that no one can keep up with the expansion of scientific knowledge. There is simply too much to know—past, present, and future. Most scientists are competent in their own special fields, and there is the handful of truly great men who contribute to more than one field of science. The majority of scientifically trained men, however, are able to assess the interaction of science and society only in an exceedingly modest way, because of their own narrow specialization. For example, scientists agree on many facts relating to nuclear fallout. They disagree on the interpretations to be drawn from these facts. The controversies which find scientists at sword's point in discussions of nuclear-bomb testing, missile propulsion systems, or even such relatively non-emotional conceptual schemes as electron orbits in atoms are well publicized; it is apparent that scientific training does not guarantee clearness of thought in all spheres of endeavor.

If these points are valid, it is inconceivable that education in science should be fact-centered and immediately practical. Science and its derivative technology are moving rapidly. Therefore, education in science should not be solely dependent on the state of technology, and must bear witness to values other than the practical. At the same time, reference to and, to some extent, reliance on the practical is both unavoidable and pedagogically justifiable.

There are other justifications for a shift of viewpoint in teaching science to meet the demands of a scientifically and technologically oriented society. We believe that the focus of science education from kindergarten to college should be on the development of ability to think critically and imaginatively in science. If science, as both dynamic process and rapidly changing product, is of value in education, it is in promoting an understanding of its own structure, values, and processes. There are undoubtedly many paths to such understanding, but it is obvious that traditional approaches to the teaching of science to the layman have failed, and, therefore, that a content and methodology must now be chosen which give promise of producing the desired results.

How is it possible to understand the meaning of science and the work of scientists unless the student is aware of the difficulties, the doubts, the false starts, and the grueling labor involved in postulating and testing new conceptual schemes that are soon altered or even forgotten? Students who learn how scientists learn simultaneously learn what science is. Instead of visualizing science as a corpus of unchanging facts and theories (product) to be memorized, students are instructed in the dynamic processes of scientific investigation: "Why?" "How do you know?" "How should we phrase this question so that a valid answer may be obtained?" Students themselves may isolate problems, invent working hypotheses, and derive from data the simplest principles or laws. In short, the focus of science ought to be on achieving a functional grasp of the language and structure of science rather than on science as a technological innovator or as a better explanation of the physical world. In the attempt to speak the language of science, the student will gain the essential goals of clear and careful thought.

Of course, it is important to know many scientific facts and principles. Everyone *ought* to know the significant content of every field of knowledge. It is reasonable to expect that the more the individual knows, the greater is the probability that he will see the relationships between the important principles and concepts of science, and thereby facilitate personal integration of science. These are important goals, but they are perhaps not as vital to society as is the goal of fostering growth of the investigative and critical mind.

The characteristics of science

How is science related to the great modern disciplines? What does it have in common with art? With literature? Every branch of knowledge, including the sciences, is permeated by some philosophical structure—the assumptions and untestable beliefs upon which the elaborate super-structure of the discipline is built. One looks at literature or art or physics from the vantage of his own frame of reference, which is the particular theory of knowledge he consciously or unconsciously holds. The very meaning of science as elucidated by Conant is philosophically oriented—there is no scientific way to validate his definition.

Mathematics, the handmaiden of the sciences, is interwoven into each of the scientific disciplines; the extent of its integration is a measure of the "exactness" of the discipline. Astronomy, physics, and chemistry are "exact" in this sense. Biology, psychology, and the social sciences, in that order, are markedly less so. On the other hand, the humanities are demonstrably non-mathematical, although symbolic logic is essential to the study of language and meaning. At first glance, the sciences and the arts are poles apart; their lack of relationship is much less clear-cut on further analysis. Each discipline shades gently and imperceptibly into its neighbors. Behavioral zoologists study the sociology and psychology of animals. Archaeologists derive new insights from the rapid advances in chemical and physical analysis. Biology draws on chemistry, physics, and geology. This is to be expected. But in addition, science also demands of its practitioners a high order of ability to read and write. Without communication, science reverts to the mystery of its alchemical ancestry.

Today, new field-crossing disciplines are emerging. The union of physical science and biology is commonplace in the person of the biochemist and biophysicist, and in the discipline of the biophysical sciences. Scientific research is pursued by the research group, a relatively new organizational structure, composed of men and women each of whom contributes specialized skills and knowledge. In cancer research, for example, groups commonly include physical chemists, biochemists, biophysicists, electrical engineers, medical doctors, physiologists, microbiologists, and pathologists. The change from individual investigator to team effort is a remarkable stimulus to scientific advance. Despite these integrative forces which blur traditional distinctions, it is possible to characterize science so that, as the term is used in this book, it has a more or less precise meaning. It is an enterprise in which the distinctive operations and attributes analyzed below are consistently to be discerned. This operational structure is a grossly simplified model of scientific endeavor, and it is therefore proposed as a suggestive outline only.

Quantification

One of the most fundamental characteristics of science is its dependence on quantification. The scientist accords questions of measurement the highest priorities—"Whatever this phenomenon is, can it be measured? How rapidly does it change? How fast does it move?” If measurement is impossible, the scientist is likely to turn to more fruitful topics. This does not mean that measurement is ignored in nonscientific endeavors. There is, for example, a kind of measurement involved in judging literature or art, because comparisons must inevitably be made, and measurement is comparison. But the scientist has an advantage in that his measurements are made with rulers of constant length. Under ordinary conditions, a yardstick will reproduce the same length for a table (within certain limits of error) time after time. Few individuals, however, have the capacity or desire to retain unchanging critical standards in judging paintings. There are no fundamental, accepted units of value, of interest, of satisfaction, or of style; and different judgments from generation to generation and from critic to critic are the rule. This does not imply that non-changing (invariant) measuring instruments make science “better” than the humanities. These instruments simply make science more convenient and objective, and this is why scientists are unwilling to study phenomena which are, at best, only semi-quantitative.

Why is science so difficult for so many students? Why has so much knowledge been amassed in science with no end in sight? Ponderous volumes dealing with one phase of the chemistry of a single element have been written, each seemingly so complete that the reader intuitively and erroneously assumes that nothing more need be said. But even before publication, the information they contain is behind the times. The mathematical treatment of data, and the theories derived from such data in the so-called exact sciences of physics, astronomy, and chemistry, present a formidable obstacle to students. Even in the mathematically less rigorous studies of biology and psychology, statistical formulae are commonplace. Yet, unless the phenomena studied are well understood and are relatively simple, it is impossible to propose mathematical models which lead to practicable solutions. There are excellent treatises on the physics and physiology of light and color, yet art is almost completely non-mathematical. Is this not because art, as a supreme expression of human feeling and intellect, is much too complex for mathematical analysis? Is not this complexity also the rule in economics, psychology, and sociology—the “social sciences”?

Measurement, as practiced in the sciences, and the mathematics by which the data of measurement are manipulated are important because they simplify relationships. A mathematical law is much more easily learned and applied in symbolic form than when expressed in words. For example, $E=hF$ may be stated in this cumbersome fashion: “The size of a quantum of energy emitted by an atomic oscillator is equal to a constant h multiplied by the frequency of the oscillator.” The formula may be manipulated in accordance with the laws of mathematics much more easily than its verbal equivalent. The very simplicity of the mathematical expression multiplies its usefulness immeasurably, but this convenience is unavailable to the other, less linear disciplines.

This is not intended to disparage the social scientist, nor is it an arrogant attempt to crown the chemist or physicist as the victor in a gratuitious "search for truth." It is simply a reflection of the massive difficulties which face the student of human interactions, of the obstacles which are far more formidable than the low hurdles barring the way of the physical scientist. Truly, man knows so much more about chemistry than sociology because there is so little chemistry to know. In a sense, chemistry is more intricate than sociology because chemistry is much simpler.

Observation and experimentation

The image of the scientist, carefully nourished by the movies and by television advertising, is that of an absentminded professor who, attired in a long white coat, spends every waking moment at his work. In the public mind, the scientist and science are inextricably connected with "experiments" which are carried on in dark, rather frightening rooms called laboratories. There is a certain degree of validity in this conception. Experimentation and the rigorous observation with which it is associated are keystones of scientific endeavor. As a result, science is qualitatively distinguishable from the other disciplines because its observation and experimentation are carried to an extreme. Although rigorous observation is essential to many life pursuits, it is only in the natural sciences that controlled experimentation flourishes. For the purposes of this discussion, the experiment is defined as a planned variation of the conditions in which a certain phenomenon occurs in order to reveal what effect these variations have on the phenomenon.

Experimentation is typically frustrating and difficult to pursue because the experimenter is combating what has been described as "the cursed perversity of inanimate matter." There may exist unknown variables (factors capable of affecting the results) and assumptions of which the experimenter is unaware. The experimenter's apparatus may be insensitive to the particular event, or may actually affect it in some unexpected way. A classic example of such interference is the characteristic appearance of certain "structures" in bacteria which have been chemically stained for microscopic study. These structures are sometimes the result of a reaction between the stain and the cell protoplasm, and have no counterpart in the living bacterium. Early experimenters, not aware of this possibility, were deceived by these structures, and came to erroneous conclusions.

The existence of difficulties such as these in the relatively simple natural sciences is a warning that experimentation of the kind employed by scientists may be impossible in the social sciences, or, indeed, in any endeavor which tries to cope with a multi-faceted, ever changing environment. Rigorous experimental control of social phenomena seems to be beyond reach. To that extent, the so-called "scientific method" is a mockery when it is applied to problems outside the quantitatively simple sciences in which the classical processes of science were nurtured.

Intensive observation of individuals and small groups is an important technique in both the social and natural sciences. The approach of the botanist who classifies plants by their structural characteristics is somewhat similar to that of the clinical psychologist. The extent to which significant generalizations emerge from individual and small-group analysis is quite different, however. As a result, the statistical-probabilistic mode of operation, which is useful in the life sciences, is absolutely essential in the social sciences.

The term "experiment" should denote a certain kind of experience. Manipulation of scientific apparatus is not necessarily an experiment. In experimentation, a genuine problem or question exists, and the experimentation is an attempt to discover or test possible relationships, causes, and effects. If, on the other hand, the purpose of the procedure is to verify that which is already known, as is all too often the case in stereotyped instruction, it is more appropriate to speak of a laboratory "experience," and reserve "experiment" for more creative activity.

The scientist generally finds it necessary in experimentation to rely on controls which he defines as "similar test specimens . . . subjected to as nearly as possible the same treatment as the objects of the experiment, except for the change in the variable under study."[5] If, for example, he desires to test the hypothesis that calcium is required for normal growth in chicks, the experimenter compares the growth rate of chicks divided randomly into control and experimental groups. The control group, which is given a "normal" diet, is contrasted with the experimental group, which is fed a low-calcium or a calcium-free diet. Every condition is the same for the two groups with the exception of the presence or absence of calcium in the diet. But even with these precautions, the effects discovered may merely be chance variations, or perhaps may be the result of an undiscovered error which affects one group more than the other group. As a case in point, the chemical removal of calcium from foods may result in a loss of other necessary minerals or vitamins, and this added deficiency may cause a more significant change than the elimination of the calcium by itself. The probability of chance variations or of experimental error may be estimated statistically and thus furnish significant information to the experimenter. Procedural errors, on the other hand, may be discovered by using other experimental techniques for removing calcium which affect nutritional materials differently and thus lead to contradictory results.

In general, more than one trial or experimental run is necessary in order to detect errors and to estimate precision of measurement. The experimentalist must beware of the "chick-growth" experiment which purports to "prove" the value of calcium by its effect on two or three chicks. "A story is told of an investigation in which chickens were subjected to a certain treatment. It was then reported that 33⅓% of the chickens recovered, 33⅓% of the chickens died, and no conclusions could be drawn from the other 33⅓% because that one ran away."[6] If it is necessary to rely on a few poorly chosen specimens because only these few are at hand, the experimenter should be duly suspicious of the results, and limit his highly tentative conclusions to those few chicks. Conclusions may be extended to a general population only if the experiment is well controlled and the specimens are randomly selected from that general population. The typical plant or animal experiment in the schools seldom satisfies these conditions. Therefore, caution in generalizing must be a watchword! Children are prone to jump to superficial conclusions, and their teachers must continually be aware of the strict necessity of fitting generalizations to the data. The theory of experimental procedure is complex, and it is not feasible to discuss laboratory experimentation in detail at this point. The suggestions which are provided in Chapter 7, "Firsthand Experiences," will guide school experimentation to reasonably valid conclusions.

Prediction

A third characteristic of science, the requirement for quantitative prediction, is founded on the belief that nature is orderly. Once this order is known, quantitative predictions can be made. Although some scientific theories—evolution, for example—are not in themselves capable of generating predictions by which they may be tested, scientists accept the validity of most theories only if they are fruitful. If we believe that green plants manufacture food only in the presence of light, it is reasonable to expect that variations in light intensity or quality will affect the food production of plants in predictable ways. In repeated tests of this hypothesis, food production in plants has stopped in the dark, and as a result the hypothesis is strengthened, although it is not proven. Indeed, the hypothesis can never be proven in the sense that a geometrical theorem is proven. The best that can be done is the establishment of a high degree of probability that a hypothesis is valid.

The value of prediction in testing the validity of a hypothesis is well illustrated by the history of the discovery of the planet Neptune. At the time of this epochal event, it was assumed by astronomers that the planets revolved around the sun in elliptical orbits. If the laws of planetary motion which had been formulated by Kepler and Newton in the seventeenth century were valid, then a planet whose observed position was not the same as that predicted by these laws must be affected by an unknown force. What was this force? In the early 1840's, U. J. J. Leverrier, a French astronomer, and J. C. Adams, a young Englishman, attempted independently to answer this question for the planet Uranus. Numerous observations by competent astronomers in the decades following the discovery of Uranus were almost unanimous in assigning positions to the planet which were inconsistent with the positions predicted by the laws of planetary motion. Leverrier, relying on these laws, was able to show that this strange behavior of Uranus could not be explained by a rational application of the planetary laws as they were then conceived.[7] There was no reason to question these laws. Had not several attempts to discredit them failed ignominiously? Leverrier therefore determined to discover the reason for the irrational behavior of Uranus. Other astronomers had previously contemplated the existence of a planet beyond Uranus, which, by virtue of gravitational attraction, could pull Uranus out of its normal orbit; no one, however, had successfully grappled with the difficult mathematics which were required. In 1845, Leverrier defined his problem in these words:[8]

> Is it possible that Uranus' inequalities may be due to a planet located in the ecliptic; at a mean distance double that of Uranus? and were this so, where is the planet now? What is its mass? What are the elements of its orbit?

In order to solve the problem facing him, Leverrier was compelled to reverse the classical method of astronomical analysis, in which the known mass and orbit of a planet are applied in computing its pull on another planet, and instead to infer from the mass and orbit of the disturbed planet the nature of the disturber. This procedure is analogous to deducing from a given conclusion the set of premises from which the conclusion was drawn, a much more difficult process than the derivation of a conclusion from a given set of premises.

Leverrier worked feverishly for a year to find a suitable solution. In 1846, he was so sure of his hypothetical planet that he requested Dr. J. G. Galle, a Berlin astronomer, to search for it. Leverrier boldly predicted not only the position and apparent diameter of the planet, but its density and mass as well. Within an hour after receiving the letter, Galle discovered an unrecorded eighth-magnitude star which changed position during the next twenty-four hours. This star was not only within one degree of the predicted position, but its apparent diameter was almost identical with Leverrier's proposed planetary diameter.

Galle's letter to Leverrier confirming the existence of Neptune is reproduced:[9]

> The planet which you described really exists. The very day on which I received your letter I found a star of the eighth magnitude which was not charted on the excellent . . . map published by the Royal Academy of Berlin. Observation on the following day decided that it was the searched-for-planet.

This spectacular accomplishment, the discovery of a new world, was fittingly described by the English astronomer G. B. Airy in these words: "Nothing . . . so legitimately bold [since Copernicus' work] has been enunciated by way of prediction."[10] Ironically, J. C. Adams, Airy's countryman, had solved the problem before Leverrier, but by a strange combination of circumstances was unable to obtain a hearing of his work before Leverrier made his announcement.

Surely, such an extraordinary achievement exemplifies the inductive and creative facets of science, even though we now know that it was somewhat flawed by a number of chance factors (unknown to Leverrier) and simplifying mathematical assumptions which collectively and coincidentally made success possible. The magnitude of this success vindicated Leverrier's faith in the validity of the classical laws of planetary motion, and stilled for years to come any further questioning of these laws.

There is, however, an instructive comparison to be made between this triumph and the bitter failure which Leverrier experienced a few years later. Prior to his master stroke with Neptune, Leverrier had struggled to explain a noticeable discrepancy in the orbit of Mercury. He returned to this problem with renewed vigor, and soon concluded that the orbit of Mercury was changing (precessing) by a small but fixed value each century. Known planetary orbits failed to account for this difference. Was it possible for the same Newtonian mechanics which had been so dramatically vindicated only a few years before to be wrong in this case? Leverrier could have resolved his problem by changing the estimated mass of the planet Venus by a factor of one-tenth of the accepted value, but hundreds of reliable observations and calculations ruled out the possibility of a 10-percent error. To Leverrier, the only feasible explanation was a "deus ex machina," another unknown planet which, moving between Mercury and the Sun, disturbed Mercury's orbit just as Neptune disturbed Uranus. The new planet was christened Vulcan, and astronomers were exhorted to search for it.

A large number of sightings were reported. Few were recorded by professional astronomers, although one scientist, the discoverer of twenty planetoids, reported that on July 29, 1878, he had personally observed two intra-Mercurial planets during an eclipse. No other astronomer, of the hundreds who witnessed the same eclipse, confirmed this observation. Indeed, there has never been a confirmed observation of the Vulcanian planet which exhibits the characteristics attributed to it by Leverrier.

Why was Newtonian mechanics so successful in the case of the extra-Uranian planet and apparently so wrong in what appears to be a completely analogous situation? N. R. Hanson, the eminent philosopher of science, maintains that Leverrier was led astray by his faith in the theoretical structure of astronomy.[11]

> The man holding the stakes in both cases was U. J. J. Leverrier. The triumph was his; he drew from the theory what few suspected it possessed. But the failure was not his—it was the theory's. He pressed it onto the problem of Mercury, just as Neptune had taught him to do. But it could not bring forth results which it did not possess.

The anomalies of Mercury's orbit remained unexplained until Albert Einstein formulated his general theory of relativity in 1916. This great theory denies the precise and universal validity of classical Newtonian mechanics, which is, indeed, a special case of the general theory. The close agreement between general relativity's prediction for the change in Mercury's orbit and the observed change marked the first major success of non-Newtonian planetary theory. As a result, it is unnecessary to postulate an intra-Mercurian planet, and thus the planet Vulcan perished ignominiously.

The moral to be drawn from this episode in the history of science is that scientists validate their hypotheses, in so far as they can be validated, by agreement between predicted and observed behavior. If close agreement is not found, the investigator must review his assumptions and procedures carefully. Is the hypothesis faulty? Are the observations correct? Or, is the experiment improperly designed to test the hypothesis? Scientists are exceedingly reluctant to abandon a cherished hypothesis or theory even though it is contradicted by the facts, and do so only because there is no other alternative. It is probably a truism that the value of a hypothesis is ascertained only by its consequences. No matter how promising or intriguing, the conceptual scheme must be "fruitful of further experimentation and observation."

Science is cumulative

Science has been characterized by controlled experimentation, rigorous observation, "exact" measurement, and by validation of its hypotheses by the test of experience. It is also cumulative and progressive to an extent unattainable in the arts. As George Sarton, the great historian of science, once remarked:[12]

> The making of knowledge, unlike that of beauty, is essentially a cumulative process... Nothing that has been done or invented gets lost... This cumulative process is so obvious that even very young men may be better informed and more learned than their more illustrious predecessors and so they have a chance to see further.

Cumulation is possible only because science is self-correcting. Despite the vigor of argument and counter-argument, a consensus is sooner or later achieved. Darwin's theory of natural selection was fiercely debated for decades following its publication in 1859. Not until after the turn of the century was natural selection internationally accepted by scientists. Literally thousands of controversial proposals have been published; sooner or later, sufficient evidence has accumulated to permit acceptance, rejection, or modification, and eventual integration into the body of scientific knowledge. Errors are soon exposed by the natural course of scientific growth, and the appropriate adjustments are made. If a chemist misreads a temperature, or a biologist mistakes one structure for another, his peers soon expose his mistake by the merciless tribunal of objective experiment. This evaluative process is feasible today only because of the existence of thousands of scientific research publications. Such well-known attributes of the scientist as honesty, accuracy, and thoroughness are, in a somewhat trivial sense, forced upon him because of his realization that his work, and with it his reputation, is in the public domain. The scientific endeavor can build on past triumphs because past error has been eliminated. The rapidity of the corrective process is immeasurably increased by the existence of a well-financed, closely-knit, international community of scientists:[13]

> [There is] an organization of individuals in close communication with each other. Because of the existence of this organization new ideas spread rapidly, discoveries breed more discoveries, and erroneous observations or illogical notions are on the whole soon corrected. The deep significance of the existence of this organization is often completely missed by those who talk about science but have no first hand experience with it. Indeed, a failure to appreciate how scientists pool their information and by so doing start a process of cross fertilization in the realm of ideas has resulted in some strange proposals by politicians even in the United States.

Literature, art, music—few, if any, of the non-scientific disciplines are self-correcting in this sense. Is it meaningful to speak of an error in a Schoenberg composition, a Pollock abstraction, or a Trollope novel? Of course, styles and critical fashions change, and there is a sense in which their ebb-and-flow is "error correction." The difference, however, is that science is self-correcting because it is inherently a non-controversial, objectively analytical, coherent body of knowledge. The arts, on the other hand, are so complex in their subjectivity that the rigorous criteria which define science are irrelevant and undesirable. The very notion of an irreversible process of self-correction in the arts is repugnant. But, more to the point, it is impossible!

Process

"The scientific method" is one of the most overworked and hackneyed phrases in the literature of science and science education. Unfortunately, many people believe that "the scientific method" is the scientist's "philosopher's stone," and that the conscientious application of the method is sufficient to resolve the difficulties confronting the researcher. It is tempting to say that scientists are agreed that there is no "scientific method"; that it exists only in the writings of those who have either overlooked the new philosophy and history of science or have never pursued scientific research. The phrase, however, still appears with some regularity in scientific literature, and it is obviously not withering into oblivion. In science education, the analyses of "scientific method" by Karl Pearson and John Dewey are the philosophical foundations of most textbook discussions. Few science texts omit a token mention; many describe in some detail the logical steps which are given below as the method presumably followed by scientists:

"The Scientific Method"

1. Identification and statement of the problem.
2. Formulation of hypotheses.
3. Search for evidence to test hypotheses.
4. Assessment of validity of hypotheses.
5. Revision of hypotheses if necessary.
6. Application of conclusions to similar problems.

How simple and concise! How attractive as a guide to the perplexed! Unfortunately, this skeletonized codification of scientific process is deceptively difficult. It is of value as a logical analysis of scientific investigation, but it is not an infallible guide to action, and it should be contrasted with these often quoted words of Nobel Prize winner P. W. Bridgeman: "The scientific method, as far as it is a method, is nothing more than doing one's damnedest with one's mind, no holds barred."[14]

If "the scientific method" is really a dependable guide to action, why have scientists been so slow in resolving some familiar and vexing problems? Why did it take more than one hundred years of persistent and frustrating research to synthesize quinine? Benjamin Franklin equated lightning with static electricity in 1752. Why, then, is there still no general agreement on the causes of lightning? Scientific discovery should quickly follow the logical and intelligent application of "scientific method"; such achievement, however, is clearly not inevitable. There is no simple guide for creative discovery, nor are these rules for tearing loose nature's secrets binding on nature. In Conant's words:[15]

> The stumbling way in which even the ablest of the scientists in every generation have had to fight through thickets of erroneous observations, misleading generalizations, inadequate formulations and unconscious prejudice is rarely appreciated by those who obtain their scientific knowledge from textbooks.

A classic example of these struggles is readily at hand in the work of Gregor Mendel, the Moravian monk, whose years of labor in breeding plants laid the foundations of the science of genetics. Mendel published his results in the rather obscure journal of his local scientific society in 1866. No one paid any attention to it. Mendel wrote the leading German biologist, Karl Nägeli, describing his results, and asking for help. Nägeli, after a long delay, rejected his ideas. Not until the turn of the century was Mendel's work recognized for its interpretative power. It is difficult to explain why his brilliant insights were unrecognized by his contemporaries. Perhaps it was because biologists were busily engaged in asking questions which had little relevance to the problems with which they were confronted, and because they scorned amateurs such as Mendel who were not members of the establishment.

In the physical sciences, the early history of X-rays is even more remarkable. Some years prior to Roentgen's discovery of X-rays in 1895, Sir William Crookes, a world-famous experimental physicist, noticed that unexposed photographic plates in his laboratory were often fogged and consequently useless. Crookes was eminently qualified to investigate the action of the Crookes tube, which, unknown to him, emitted X-rays; but somehow he missed connecting the tube with the fogged film, and was thus deprived of the triumph of discovering X-rays. Lord Rayleigh, himself an eminent physicist, is the source of this anecdote concerning Crookes:[16]

> It was a source of great annoyance to Crookes that he missed the discovery of X-rays. According to an account he gave in my hearing, he had

> definitely found previously unopened boxes of [photographic] plates in his laboratory to be fogged for no assignable reason, and acting, I suppose, in accordance with the usual human instinct for blaming someone else when things go wrong, he complained to the [makers], who naturally had no satisfactory explanation to offer. I believe it was only after Roentgen's discovery that he connected this with the use of highly exhausted vacuum tubes in the neighborhood.

Still more startling is the fact that two American physicists took the first X-ray photographs in 1890, five years before the discovery of X-rays. They saw nothing novel in their results; not until 1896 were their plates re-examined, and the true significance of their inadvertent achievement understood.[17]

> [Roentgen alone] discovered the existence and nature of x-radiation. The discovery was in the air—at the very fingertips of dozens of scientists who might have made the same discovery. "The seeds of great discoveries are constantly floating around us" the famous American physicist Joseph Henry once wrote, "but they only take root in minds well-prepared to receive them."[18]

If Roentgen had missed X-rays, it is certain that another physicist would have made the discovery within a few years.

These instances should be sufficient proof that innovation in science is not necessarily attained by simply following the steps of "the scientific method." It is probably true that published accounts of scientific research exemplify "the scientific method," but invariably they omit the problems of strategy which confronted the researcher—how he recognized and defined the questions to be answered, how he created his hypotheses and decided on the experimental and observational situations which tested them. "The scientific method," in other words, is a logical analysis of scientific research, but it is an analysis after the fact. It does not tell us *how* each step is to be attained, or how to advance from step to step.

Scientific progress may evolve from exhaustive exploration of all possible alternatives—for example, Goodyear's discovery of rubber vulcanization and Ehrlich's synthesis of the anti-syphilis drug, Salvarsan. But the advances which revolutionize science rarely arise from hard work alone. Breakthroughs are more often the result of acts of scientific creativity, of chance events, or of the availability of new instruments without which advance is impossible. The first-rate scientist often speaks of the role of intuition, hunch, chance thought, and the lucky accident in his research. Charles Nicolle, who first recognized how typhus was spread, wrote about this "sudden flash of creative illumination . . . This shock, this sudden illumination, this instantaneous self-certainty of a new fact—I know of it, I have experienced it in my own life."[19]

This "creative illumination" is frequently the result of a chance event, as in the discovery of penicillin by Sir Alexander Fleming. In September 1928, Fleming observed that one of his bacteriological cultures had been contaminated by a penicillin mold. Contamination of this kind was not uncommon, and the imperfect culture was customarily discarded without delay. Fleming, however, examined this particular specimen carefully and noticed that the bacteria near the mold had disappeared. For some reason, he was struck by this event, and decided to find out why.[20] Fleming intuitively concluded that the mold was secreting some substance inimical to bacteria, and designed a systematic experiment to test his hypothesis. Eight months later, he published his now famous results in *The British Journal of Experimental Pathology*. He had not been the first to observe the bacteria-destroying activity of a mold; such effects had been reported as early as 1875. But he was the first to propose and test a hypothetical explanation which was "fruitful of further experimentation and observation." The workings of chance are illustrated by the fact that the cultured bacteria were staphylococci, a strain particularly sensitive to penicillin.[21]

This brief sketch of penicillin's discovery has been much oversimplified. Chance factors, after all, were but *one* aspect of the total picture. Fleming had long been interested in the treatment of bacterial infection; he had previously discovered by a brilliant series of experiments the anti-bacterial enzyme lysozyme. His was, in Pasteur's well-known phrase, "the well-prepared mind." New chemical techniques of separating and concentrating the penicillin mold secretion were also essential. Had Fleming failed in his investigation, the end result would sooner or later have been the same. Someone else would have succeeded. It is reasonable to believe, however, that penicillin was made available to the world many years before a systematic study of possible antibiotics could have revealed its existence.

The atmosphere of scientific endeavor is such that significant discoveries are frequently announced at about the same time by independent investigators. The almost simultaneous discovery by Hall, an American, and Herroult, a Frenchman, of the modern process of extracting aluminum and the discovery of electromagnetic induction by Faraday in England and Henry in the United States, to cite but two cases, prove that scientific ideas, if the time is right, are "in the air," and are seized on by those men who are "well-prepared." This phenomenon of independent investigation is characteristic of science, and therein lies a major dissimilarity between science and the arts. There are no unique creations in science—no masterpieces beyond the ability of other humans. The world without Shakespeare would be a world without *Hamlet;* there would be no *Eroica* without Beethoven; but the general theory of relativity, differently named but essentially the same in structure, was virtually certain of creation had Einstein not existed. Newton's law of gravity, "one of those triumphs that humble ordinary men in the presence of genius," had already been foreshadowed by such men as Robert Hooke and Edmund Halley, and would assuredly have been formulated by some other scientist within a few decades following 1687, the year in which Newton gave his work on planetary motion to the world.[22]

Because there is no infallible road to success in science, we should be careful to think of "the scientific method" as a guide which can point out the road, but cannot guarantee safe passage. The task of the creative scientist is to find "likeness in unlikeness," "order in disorder." How reminiscent these phrases are of Coleridge's famous definition of beauty as "unity in variety," and his dictum that in the creation of beauty lies the task of the poet. In a literal sense, both poet and scientist are creators. Their mission is revealed in Melville's poem, "Art":

> What unlike things must meet and mate:
> A flame to melt—a wind to freeze;
> Sad patience—joyous energies;
> Humility—yet pride and scorn;
> Instinct and study; love and hate;
> Audacity—reverence. They must mate,
> and fuse with Jacob's mystic heart,
> To wrestle with the Angel—Art.

The great scientist cuts through the mass of facts which encompasses him, and finds or, perhaps better, invents an "order" which cannot be revealed by observation alone. This order does not exist in nature—it is a free creation of the human mind. Jacob Bronowski, in his magnificent essay on human values in science, reminds us that John Dalton, the great English chemist of the early nineteenth century, was visionary enough to fuse the Greek image of the atom with the chemical facts of the late eighteenth century.[23] Dalton is the "inventor" of the modern atom. His creation required the same leap of sensibility and imagination by which the artist fuses certain selected elements of his universe into a new transcendent synthesis. Dalton's synthesis was a supreme leap of the scientific imagination.

The importance of Dalton's achievement is undiminished by the fact that his conceptual scheme has been so changed that he would not recognize it were he alive today. Change is inherent in science, and Dalton's ideas have long since been assimilated into modern atomic theory. His theories marked one of the turning points in the relatively short history of chemistry.

Imagination, perception, and a feel for a possible unity between seemingly unrelated facts and concepts are qualities which distinguish the creative from the non-creative toiler in the scientific vineyard. In none of the notable achievements described above is it possible to distinguish the strict application of "the scientific method." Assuming that a problem has been isolated and clearly defined, a task which is frequently of the greatest difficulty, the next step, if we follow "the scientific method," is to formulatė an explanatory hypothesis. Unfortunately, it is just at this time, when creative imagination is most essential, that the "method" is the least helpful. Once the hypothesis has been devised, most scientists are able to invent ways to test it by exploring pertinent facts and by careful observation and controlled experimentation. But these activities, although not routine, are relatively less challenging.

Values

What makes a scientist? Why does he choose a career which requires such long, arduous training? What keeps him to the grindstone of research year after year, despite his expectation of almost continual failure? How does he dare confront the public whose image of the scientist has in the past been so unflattering:[24]

> He is a brain; he is so involved in his work that he doesn't know what is going on in the world. He has no other interests and neglects his body for his mind. He can only talk, eat, breathe, and sleep science.
>
> He neglects his family—pays no attention to his wife, never plays with his children. He has no social life, no other intellectual interest, no hobbies or relaxations. He bores his wife, his children and their friends . . . with incessant talk that no one can understand.

Rather extensive psychological and sociological research describes the scientist (in direct contrast to the engineer and technician) as strongly self-directed; a person who prefers situations which challenge his intellect rather than his emotional or social skills. He is personally dominant, but avoids controversy. Independent of group pressure, he is characterized by high intelligence, early interest in intellectual performance, and a strong drive to find relationships between the phenomena in which he is interested. There is good reason to believe that scientists are "born," not made, and that their psychological characteristics tend to develop at an early age. Therefore, it is possible that the scientist is undeterred by public opinion because, as an outsider, he has learned to ignore "the slings and arrows" of his socially-centered peer culture.

The derogatory quotation cited above is a product of the adolescent mind. But many literate, sensitive adults are also repelled by the world of science. George Gissing, the nineteenth-century English novelist, expressed the attitude of many:[25]

> I hate and fear "science" because of my conviction that for long to come if not forever it will be the remorseless enemy of mankind. I see it destroying all simplicity and gentleness of life, all beauty of the world; I see it restoring barbarism under the mask of civilization; I see it hardening men's minds and hardening their hearts.

These stark, disturbing words express an awareness of only the negative aspects of technological advance. C. P. Snow, the contemporary scientist-novelist, has coined the phrase "the two cultures" as an epithet for the division of literate men into science-minded and humanities-minded groups. Humanists are witheringly critical of science and scientists because they assume that scientific and human values are incompatible. Their rejection of the thesis that science is a part of man's cultural heritage, with an intellectual history and liberating energy of its own, is perhaps a reflection of the didactic, textbook-oriented science of their school years.

Obviously, scientists avoid value judgments in their work because such judgments cannot be tested in the same way and with the same precision as scientific fact. This does not mean, however, that values play no part in scientific endeavor. Albert Einstein once wrote these provocative words:[26]

> ...Even though the realms of religion and science in themselves are clearly marked off from each other, nevertheless there exist between the two, strong reciprocal relationships and dependencies. Though religion may be that which determines the goal, it has, nevertheless, learned from science, in the broadest sense, what means will contribute to the attainment of the goals it has set up. But science can only be created by those who are thoroughly imbued with the aspiration towards truth and understanding. This source of feeling, however, springs from the sphere of religion... Science without religion is lame, religion without science is blind.

Such values as truth, independence, freedom, and tolerance are implicit in the scientific heritage; they originate in man's subjective needs and aspirations, not in the physical realm of the sciences. Truth is essential because scientists must rely on the cumulative activities of their colleagues, past and present. Truth to fact, unbiased, unadorned, must exist because science itself will perish if founded on error. The

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self-correcting aspect of science guards against continuing and pernicious error. Because truth is necessary, independence, originality, and freedom of dissent are prized. The scientist must have the courage to disagree with the established order; that is, to be a non-conformer. Copernicus and Galileo at great personal risk dared challenge the Aristotelian geocentric universe which had endured for fourteen centuries. The Austrian physician Ignaz-Philipp Semmelweiss (1818–1865) was driven from his medical practice by the obstinate medical practitioners of Vienna for his advocacy of antiseptic precautions in surgery. Darwin forced a revolution in scientific and religious thought through his publication of *The Origin of Species* in 1859, a revolution in which he was to suffer personal abuse and ridicule.

Free, independent thought is possible only in a society which values freedom. Therefore, science can flourish only if free inquiry, free thought, free speech, and tolerance are encouraged. The relative freedom accorded scientists in the Soviet Union today, in contrast with the restrictions imposed on the average Russian citizen, is indicative of this profound need.

In science, there must be no distinction between the ends sought and the means by which they are sought. The perversions of Nazi medicine in which human life was sacrificed on the altar of research are unimaginable to men and women steeped in the scientific tradition. Many scientists today on both sides of the Iron Curtain idealistically refuse to carry on research with weapons of destruction because of their awareness of the responsibility invested in them. Indeed, the values of science are not merely contemplative and philosophical, nor are they absolutes which man can never truly apprehend. Their very existence is fundamental to the pragmatic demands of the search for truth, a search which survives and prospers only in the free society.

Science today, as in the past, is an international enterprise. There is no French chemistry, no American physics, no Danish astronomy. The distribution of Nobel awards in chemistry, physics, and medicine is irrefutable evidence of a world community in science. In a very real sense, science is a society open to all who are prepared for it—prepared by virtue of a rigorous training and a dedication to its value system.

Structure

Modern theories of teaching science stress student cognition of the structure of science. The "structure of science" is a currently fashionable figure of speech which is nothing more nor less than Conant's "interconnected series of concepts and conceptual schemes." It is, in other words, the conceptual scaffolding uniting the observable phenomena of our universe. Compare this emphasis with such earlier expressions of purpose as "enhancing student understanding of our environment" or "understanding the role of science in technical innovation," which are still important functions of contemporary science education. To be scientifically literate is to comprehend the language of science—yet such skill is attainable only by an understanding, on the learner's highest level, of the conceptual interrelationships of the sciences.

Consider, for example, the familiar kinetic-molecular theory of matter, which makes intelligible such apparently different phenomena as the semi-permeable membrane and the lowering of the freezing point of water in an automobile radiator when antifreeze is added. The theory is not directly connected with these phenomena; that is, it is not specific to them alone; but it does make possible their prediction and, by definition, it explains their occurrence. The student who has mastered the concepts and assumptions of kinetic theory is better able to explain other related phenomena. Once a principle is understood, it may be drawn on for new explanations. Indeed, how, except by successful application to unfamiliar situations, is evaluation of understanding possible? This behavior is a kind of transfer, but it is much more than transfer of the simple skills or identical elements postulated in classical theories of transfer. The generality of the fundamental ideas of science, their structure in other words, is what gives meaning to and control over nature.

Assuredly, specific facts are quickly forgotten. The masses of detail—densities, specific heats, taxonomic minutiae—which overwhelm the student in his study of science are retained only by virtue of extraordinary memory. Principles, relationships, concepts—abstractions from experience—are remembered much longer. Few individuals can identify rocks by comparing their characteristics with a mental image or memorized list of physical characteristics. Many, however, simplify identification by recalling the general differences which distinguish the common classes of rocks, psychologically a much easier task. The science of chemistry would be an impenetrable maze (compare alchemy, which was such a maze) were it not for the chemist's understanding of the relationships between the chemical elements, and of the structures of their compounds.

The psychological evidence for these statements is well-known. Educators have been aware for many years that efficiency of learning requires emphasis on principles instead of on the masses of facts from which the principles are derived. But somehow the actual business of teaching dilutes and negates learning theory so that *facts* become ends in themselves. Laws, principles, and theories are indeed important elements of science curricula, but they in turn have often become facts to be memorized and their significance in clarifying relationships has been ignored.

The words "law," "theory," "fact," and "principle" have been used intuitively in the preceding discussion. What precise meanings can be extended to these terms? How are they related to each other? How are they incorporated into the structure of science?

The world of theory Figure 1 is a simplified delineation of these relationships:[27]

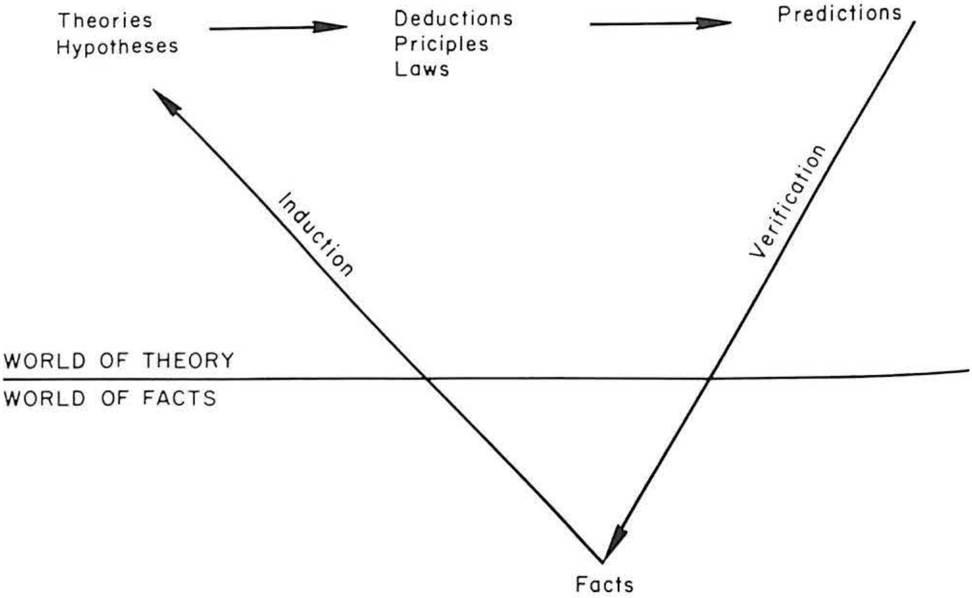

Figure 1

The reader must consider this scheme to be presented for purposes of discussion: it is not a guide to scientific research. Note that its foundation is "fact"—the recognition and observation of "a single event."[28] Hypotheses and theories are abstracted from observable facts. From these hypotheses and theories, principles and laws are deduced. Predictions may then be made which are verified by comparing them to the world of observable fact. The fact is a particular item of information. It is a fact that chlorine is a gas at room temperature and normal atmospheric pressure. It is also a fact that chlorine is yellow-green under these conditions. From facts such as the normal gaseous state of chlorine, its change under pressure and low temperature to the liquid or solid state, its ready diffusibility, and its volume decrease under pressure, it is possible to derive a theory that chlorine is composed of particles (molecules) which are in rapid motion.

A theory may be defined as a report of an "unlimited, perhaps infinite, number of events." A fact is a particular item of information, whereas a theory is general, a higher order of abstraction from experience. The scientist can convert chlorine from the gaseous to the liquid state under certain conditions. This can be done anywhere, with any chlorine molecule, and the theory of the molecular composition of chlorine applies to all chlorine. Not only must theories associate facts in a coherent and meaningful way, but they must predict and "explain" these facts. Theories are not automatically and effortlessly derived from experimental and observational data. In Nagel's words, theories are "free creations of the mind"—achieved by a relatively small number of creative scientists. Theories are accepted, not because scientists believe in the necessary existence of the ideas associated with the theory, but because the theory relates, explains, and predicts the greatest variety of observational and experimental data in the simplest and most economical fashion.

For example, think about the concept symbolized by the word "molecule." A molecule is not directly observable. It is not a fact of experience. It is an assumption which cannot be confirmed by direct observation of whatever a molecule is thought to represent. But the concept of "molecule" as it is used in molecular theory "explains" many apparently unrelated phenomena such as diffusion, pressure-volume changes, the different states of matter, and differences in the characteristics of chemical substances. Even the familiar electron is an idea, a concept, a construction of the mind rather than an actual existing particle. It probably exists, but there is no proof other than its conceptual value in explaining observable phenomena. Vacuums are idealizations—the pure vacuum exists nowhere in the universe. Force, mass, energy—all are mental constructs, "creations of the mind."

The meaning of a scientific theory was concisely expressed by J. J. Thomson, one of England's great physicists:[29]

> [My] new theory was not to be regarded as an ultimate one; its object is physical, rather than metaphysical... From the point of view of the physicist, a theory of matter is a policy rather than a creed; its object is to connect or coordinate apparently diverse phenomena and above all to suggest, stimulate, and direct experiment.

Theoretical models Another way to understand a scientific theory is to think of it as a model with which scientists may make certain testable predictions. The picture of an atom created by Niels Bohr in 1913 is well-known to all who have studied elementary science. The atom was conceived of as a miniature solar system; a positively charged nucleus played the part of the nuclear sun, and electrons (whose total charge neutralized the nuclear charge) revolved around the nucleus in fixed orbits. Electrons were restricted to these orbits unless the kinetic energy of the atomic system changed by certain specific quantities. This was a model (theory) of the atom from which was deduced an astonishing number of predictions whose validity could be tested. Although it was soon altered to meet the demands of new data, Bohr's atom is still useful to physical scientists.

A theory is not a simple, all-inclusive statement, because theories exist in hierarchies. A relatively simple theory is apt to be a component of a more comprehensive theory. For example, Kepler's three laws of planetary motion, Galileo's law of free fall, and the laws of the tides all became special cases of Newton's complete world system, as published in his *Principia*. This system, in turn, may be derived from Einstein's general theory of relativity. Each comprehensive theory is more inclusive, predicts more effectively, and is more widely applicable than lesser theories.

Interpretation of fact Theories and facts are intellectual constructions. An event perceived by the human mind is filtered and interpreted through a screen of theories of which that mind is usually not aware. What one sees through the eyepiece of a microscope does not necessarily correspond to what is actually on the slide. The frame of reference which the biologist brings to the microscope is quite different from the ideas which guide the layman; neither sees exactly the same organism. To identify a particular plant specimen as a species of Oenothera is to make a statement of scientific fact, but it is also an act of classification which depends on notions of taxonomic structure and of type species which are pure abstractions. The concept of absolute reality, whatever it may mean to the philosopher, is meaningless in science.

Hypothesis The term "hypothesis" has been frequently used in this chapter. How does a hypothesis differ from a theory? For the purposes of this discussion, a hypothesis is defined as a preliminary idea about certain relationships which connect observable events. A theory is often said to be a fairly well confirmed hypothesis, although many hypotheses are not sufficiently interpretative or explanatory to be accepted as theories. The hypothesis may be completely or partly incorrect, but it must offer a relatively simple explanation and prediction of the phenomena involved. The formulation of pertinent hypotheses is exceedingly difficult; their verification, given the necessary facts, is generally less difficult. The lifework of the scientific theoretician is the creation of hypotheses, and it is in this endeavor that he distinguishes himself.

Torricelli, a pupil of Galileo, invented the mercury barometer.

In the course of his work, he hypothesized that the variation which he observed in the height of his barometer was caused by changing atmospheric pressure. This hypothesis was confirmed by Blaise Pascal, who arranged for a barometer to be carried to the top of a mountain to test Torricelli's hypothesis. Since the air is thinner at the top of a mountain, the column of mercury in the barometer should fall. This is the simplest and most logical expectation. The height of the barometer did fall, in accordance with Torricelli's prediction, and his hypothesis has since attained the status of theory. This and other theories have been included in the kinetic-molecular theory. With the aid of the kinetic-molecular theory, it is possible to explain why a column of mercury stands approximately thirty inches under normal conditions, and why the height of the column changes from day to day.

Law A frequent source of confusion in many textbooks arises from different meanings of the term "law." A law is sometimes defined as a theory which has "been extensively tested and found valid."[30] For the purposes of this book, however, a law is defined as a description of a regular natural occurrence; it is "no more and no less than a careful record of what actually happens, [therefore] there is no possible way of violating it."[31]

In 1858, Rudolf Virchow, the great German biologist, proposed this biological law:[32]

> Where a cell arises, there a cell must have been before, even as an animal can come from nothing but an animal, a plant from nothing but a plant. Thus in the whole series of living things there rules an eternal law of continuous development, nor can any developed tissue be traced back to anything but a cell.

It summarizes many hundreds of observations and experiments—and it is still generally valid today, even though Virchow extrapolated his law to eternity. A law of biology, however, may be much less inclusive. The "all-or-nothing" law states that an "excitable" fiber such as nerve or muscle will respond completely to a stimulus as long as the stimulus is sufficient to excite it at all. This law is valid because it is a record of what happens. It is, however, a description, not an explanation.

In the realm of physics, accurate records of the distances traversed by falling objects, the times of fall, and the acceleration due to gravity provide the data from which Galileo's law of free fall can be derived. This law is usually given as $S = \frac{1}{2}aT^2$, in which S is the distance fallen, a is the acceleration of gravity, approximately 32 ft./sec./sec., and T is the time in seconds during which the object falls. This law cannot be minutely exact because it is impossible to take every variable into account. For example, it is not exact if, as is usually the case, the falling object is slowed because of air resistance. However, the probability is high that $S = \frac{1}{2}aT^2$ will be obeyed within close limits as long as air resistance is relatively small. Obeying the law is highly probable, but still only a probability, despite the rather grandiose statement cited above that "there is no possible way of violating" a law.

A law, then, is an account of a regular occurrence in nature. It may be highly quantitative, or perhaps only qualitative, but within the limits of human and experimental error it is a careful record which makes prediction possible.

Law – a consequence of theory A scientific law is often derived from theoretical considerations. Laws are *explained* by theories. Boyle's law, which relates the pressure of a gas to its volume, may be deduced from the kinetic-molecular theory. It is therefore explained by the kinetic-molecular theory, which in turn is explained by the theories of statistical mechanics, elasticity, and molecular attraction – the higher orders of this hierarchy of theories.

Empirical laws are frequently formulated in science. These are laws lacking a theoretical base, and many years may elapse before they are incorporated into the conceptual framework of theory. Indeed, Boyle's law was not firmly embedded in a theoretical structure for almost two centuries after its first formulation.

One historian of technology remarked that prior to 1850 the steam engine did more for the advancement of science than science did for the steam engine – meaning that the artisans and engineers who constructed steam engines out of their practical experience were able to do so without the science of thermodynamics. The science of thermodynamics, the theories of heat and of heat transfer, could never have developed so rapidly without the empirical technology of the steam engine.

Theory – success and failure What is the fate of a theory which satisfactorily explains and correlates all the pertinent facts of observation and experiment with but one exception? Suppose that this exception flatly contradicts a prediction derived from the theory? Does this destroy the theory, or is the contradiction so inconsequential that it may be disregarded? An excellent example for consideration is the Copernican-Newtonian conception of the solar system, which, in the early nineteenth century, had been unsuccessful in explaining the strange behavior of Uranus. Despite repeated attacks on the validity of Newton's law of gravitation, most astronomers believed intuitively that the elegance and relative simplicity of Newton's ideas were such that they must be correct, and that some other explanation must be sought. When Leverrier extracted from the theory the prediction that an extra-Uranian planet was responsible for the deviations, the theory was once again confirmed.

When, however, the disturbance of Mercury's orbit could not be reconciled with the theory, Newtonian concepts were not immediately overthrown, because they still explained and predicted more effectively than any other astronomical scheme. With the development of the theory of relativity in the early years of the twentieth century, a new, more embracing explanation of planetary motion was possible—a conceptual scheme which successfully predicted and thereby explained the deviations of Mercury.

The vision of perfect accuracy and perfect precision of observation and measurement is an illusion. Scientists approach but never attain this elusive goal. Therefore, their predictions are expressed in terms of probability. Deviation from prediction is possible and inescapable, but the validity of the theory is not destroyed by such variation. Contradictory facts may render the theory more unlikely, but do not necessarily cause its abandonment, as long as it is possible to modify the theory to explain both the new and the old facts. Eventually, however, the theory may become so complex and difficult to apply that the time is ripe for a new hypothesis. The phlogiston theory, which died in the early years of the nineteenth century, was such a theory. Its vogue of more than a century served chemical research well, despite the complications which chemists later encountered in attempting to adapt it to meet the demands of their new knowledge. Phlogiston was believed to be a substance of negative weight which existed in all combustible substances. On combustion, enough phlogiston escaped so that the final ash weighed more than the original substance. The phlogiston theory was destroyed by the theory of combustion advanced by Antoine Lavoisier a decade before the end of the eighteenth century. Lavoiser's ideas were not only in accord with all the chemical evidence, they were also simpler, less mystical, and more powerful.

Even today, the Ptolemaic conception of an Earth attended by a satellite sun and planetary system is not an impossible model. Ancient astronomers relied on Ptolemaic theory to predict the position of the known stars and planets because they found that the theory was reliable. It *was* complex. It had to be in order to correlate the numerous phenomena with which it dealt. Copernican ideas were somewhat simpler because Copernicus assumed that the sun, not the Earth, was the center of the solar system. But prior to the astronomical use of the telescope in the seventeenth century, Copernican theory was little more successful in predicting planetary and stellar motions than was Ptolemaic theory, and therefore the new astronomy was not accepted by most learned men—there was no practical reason to change. Religious and philosophical ideas motivated some of the resistance, but less than is generally thought. Only when telescopic observation proved that planetary positions were not in accord with Ptolemaic prediction (and that the discrepancy was increasing over the centuries) did Copernican ideas begin to make rapid headway. Even the great Galileo, whose enthusiastic acceptance of Copernican ideas hastened the decay of the Ptolemaic scheme, was unable to demonstrate their validity.[33]

> Galileo was so impressed with the simplicity and elegance of the Copernican picture as compared with the complexity of the Ptolemaic picture that he felt emotionally that it must be true; and in the absence of a convincing physical argument, his method of discussion really amounted to little more than ridiculing the complexities of the Ptolemaic system.

Scientific explanation

It is always possible to question an explanation, to ask "Why?" again and again. Sooner or later, no matter how knowledgeable, the oracle must admit that his ultimate answer is grounded on faith. Why does a magnet pick up a needle? Why does an apple fall to the ground? Why is the rainbow colored? These questions are a search for explanation which may be meaningfully pursued up to a point, ultimately expiring in the blind alley of unsupported assumption, or blocked by the statement that "we do not know why." The meaning of "explanation" in science is quite different from its popular usage. The scientist explains a particular event, fact, or phenomenon by deriving its existence from theory. That is, he predicts that a particular event must occur under certain conditions because of its logical relationships in a conceptual scheme. It is not necessary for the prediction to be a new, unexpected event. It is only necessary that the prediction (explanation) emerge logically and systematically from theory.

It will be helpful to describe in further detail the factors which make up a scientific explanation. First, the phenomenon in question must be included in the domain of a theory or theories which are well validated. In addition, certain facts independent of the phenomenon must be known. Finally, the explanation must follow logically from the theory or theories and the independently known facts. If no valid theory is available, then the explainer must either admit his ignorance, or resort to imagination, myth or fantasy.

A common elementary-science experience is that in which a drinking glass is inverted in a water trough. As the glass is pushed to the bottom of the trough, the water level in the glass rises. How can this rise be explained? Is there a vacuum in the glass? If air fills the glass, does some of it dissolve in the water? Does the air leak out of the glass? Does the glass somehow cool off sufficiently to decrease the volume of air within it? What theories, limited though they may be, and what independent facts are required to explain the water rise? These questions are relevant to the answer given below, which is obviously oversimplified:

Theories

1. Fluids (air is a fluid) are composed of rapidly moving molecules which interact weakly.
2. Gases (air is a mixture of gases) are compressible because their molecules occupy a very small volume compared to the total volume of the gas.
3. The pressure and volume of a gas at constant temperature are inversely proportional.
4. By definition, matter occupies space.
5. No two objects occupy the same space at the same time.
6. Pressure in fluids increases directly with depth.
7. Fluids move from regions of high pressure to regions of low pressure.

Independent verifiable facts and assumptions

1. Increasing the depth of the glass increases the pressure on the air in the glass, as shown by measurements with a manometer (pressure-indicating instrument).
2. No air bubbles escape.
3. The glass is a solid; no air escapes through it.
4. Temperature changes in the system are minimal.
5. No chemical reaction between the glass, air, and water is observed.
6. The solubility of air in water is low.

From these theories and facts, it is possible to predict the rise of water in the glass, and thereby to give a scientific explanation. The volume of air in the glass must decrease as the pressure on the air in the glass increases because air is compressible and cannot escape from the glass; therefore, as the depth of the water increases, the pressure on the air trapped in the glass increases; the air becomes compressed, and the water rises in the glass because of the decrease in air volume, and because water, a fluid, moves from regions of high to low pressure.

The value of a conceptual structure in science lies precisely in the degree to which it makes prediction (explanation) possible. The example of the glass is trivial, but it does illustrate how the structure of science is "fruitful," and why modern science education addresses itself particularly to the theme of "an inter-connected series of concepts and conceptual schemes."

Summary

Science is an attempt to explain the universe by creating general theories which "predict" the observable facts of that universe. Theories are possible only because scientists assume that an order exists in nature, or, more appropriately, that man can create an order in nature from what is to the senses a state of chaos. In response to the belief of scientists that nature can be made intelligible, and facilitated by the unemotional, restricted domain of scientific endeavor, science has evolved into one of the dominant forces of this confused world. It is only one of these forces, and surely not the most important. Nevertheless, its conceptual structure, creative vitality, and immense interactive influence should demand of all literate individuals a determined effort to understand its two-fold nature—the twin aspects of process and product. Neither has meaning except in relation to the other—and without both, science must inevitably fade into technology, becoming a mechanic's art instead of an intellectual quest.

For further study

1. What is classificatory knowledge? Is it important? Is it necessary for the layman? How does it differ from "investigative" knowledge?

2. How does Simpson's definition of science differ from Conant's? Is it more relevant? Is it better? (See Simpson, George G., "Biology and the Nature of Science," *Science*, 139: 81–88, January 11, 1963.)

3. What conceptual schemes other than those described can you think of? Do they fit Conant's definition? (See Chapter 5.)

4. Is magic really as irrelevant to man as the authors suggest?

5. What are some of the technological changes which have occurred during the past decade?

6. Are the authors on firm ground when they assert that the nature of science can be understood only by active participation in science?

7. Leaf through a current issue of *Chemical* or *Biological Abstracts* in order to become aware of the volume of chemical or biological research.

8. What arguments, other than those cited, can you produce against teaching science from a technologically oriented stance?

9. Are the authors justified in stating that traditional approaches to teaching science have failed? What is meant by traditional? Failure? Success?

10. What important goals of science education have the authors omitted or slighted?

11. Can you cite any major writers who integrate science and literature in their writing? Why do you think there are so many or so few?

12. In what kind of world would measurement be impossible? What are the possible consequences in such a world?

13. Will the domain of the social sciences be conquered by scientific techniques?

14. What is *your* image of the scientist?

15. Was the last scientist you saw on TV or in the movies a stereotype? Whose stereotype?

16. Do artists experiment? Observe rigorously? Are they scientists?

17. What is a "statistical-probabilistic mode of operation"? Why is probability so important in the natural and social sciences?

18. How many times in high school and in college did you know in advance the answers to your laboratory experiments? How often was the laboratory an adventure?

19. To what extent is experimental educational research valid?

20. Why can't a scientific hypothesis be proven, once and for all?

21. What examples of scientific prediction, other than those in this chapter, can you find? Which scientific theories have been discarded?

22. Is it possible for Vulcan to exist? Is the idea completely dead?

23. To what extent are the disciplines of psychology, economics, and anthropology sciences? Use the "Characteristics of Science" as criteria in your answer.

24. Experiences with magnets are often found in elementary school science. In a typical experience with a bar magnet, certain kinds of conceptual and factual information will be forthcoming. Which theories, laws, hypotheses, facts, and concepts are likely to be involved?

25. "Explain" each of the following phenomena:
    (a) Pouring air from one glass into another under water.
    (b) The fall in height of a barometer as humidity increases.
    (c) The light generated by an incandescent lamp.
    (d) The rise of a hydrogen-filled balloon.

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2

The nature of child thought in science

The purpose of this chapter is to present those elements of psychological theory and research which are relevant to the teaching of science in the elementary schools. Although it is true that we know much less about how children learn science than we ought to know, the growth in our understanding of how they learn is both exciting and encouraging. But unless teachers are aware of the nature and significance of this research, they will be forced to rely mainly on intuition in order to adapt teaching and curriculum to their classes. We must not be disappointed, however, that few specific prescriptions and detailed directions for making this match between instruction and children are to be found in the literature of educational psychology—the art is not yet ripe for rigorous application of developmental and instructional theory. Nevertheless, there *is* a sound body of knowledge which the teacher may draw on in order to meet the child's needs and to capitalize on his learning potential.

In this chapter, we will focus on the developmental stages through which children pass and on the maturational and environmental factors which affect both the learning and teaching of science by Inquiry. We will begin with a brief discussion of Jean Piaget's developmental theory, because of its pertinence to Inquiry instruction and its power for enriching the teacher's skill and understanding in working with children.[1]

These two criteria, pertinence to Inquiry and power to enrich teaching, apply to much psychological literature. For this reason, the description and analysis of the studies which are reported in this book are more extensive than one customarily finds in science-methods textbooks. Not only do these investigations provide new insights into child learning, but they suggest many useful motivational, instructional, and evaluative techniques. For example, the interviewing procedures and the logical analysis of children's thinking which characterize Piaget's life's work are worthy of detailed study and practice by prospective teachers.

Piaget

The name Piaget will frequently be encountered in this chapter. He, more than any other contemporary child psychologist, has built a remarkable body of experimental knowledge, which is often brightly illuminated by a profound, all-embracing theory of mental development.

Piaget believes that learning is a continual restructuring of mental activity, not merely a process of adding to previous knowledge. This reworking of the mental framework is as drastic, though not as dramatic, as the metamorphosis of the pupa of the butterfly into the adult. This transmutation is dependent on such internal and external processes as growth (biological maturation), experience, and equilibration (autoregulation). *Equilibration* is a balancing, dynamic relationship between the child's *assimilation* of his world (i.e., how he incorporates what he sees into his own frame of reference) and his *accommodation* (the way his own patterns of response change with new knowledge). *Assimilation* is the process of extracting from the environment that which fits the learner. *Accommodation*, on the other hand, is the process by which his frame of reference, his customary pattern of behavior ("schema" in Piaget's words), is altered because of something in the environment. For example, no matter how intense our desire to move ahead, a stone wall in the path will force some kind of accommodation.

According to Piaget, the child passes through a number of more or less sharply defined stages in the course of his mental development. Whether these stages are qualitatively different, or merely reflect the child's ability to do more of the same thing better, is an important practical question which has not yet been resolved:[2]

> No qualitative transitions in learning ability occur at any age; and the evidence indicates that the same kinds of logical operations and problem-solving techniques are employed at all age levels, differing principally in degree or complexity.

The dilemma which confronts educators who attempt to incorporate psychological insights into curriculum and methodology is vividly illustrated by Wallach's assertion that "structural or 'qualitative' changes in thinking occur during development. The thinking of the ten-year-old, for instance, seems to involve different modes of analysis than that of the four-year-old rather than quantitatively 'more' of the 'same' modes of analysis."[3]

Up to the age of twenty-four months, according to Piaget, the child is in the *sensorimotor* period, in which his actions, primarily centered on motor reflexes and primitive responses, become progressively better differentiated and generalized. The child "intends," he differentiates between means and ends, and he responds to new stimuli. He begins to judge what he sees according to its permanence, location in space and time, and causal relationships. From the age of two to eleven or twelve, the child lives through the period of *concrete operations.* Up to the age of four, he is in a *preconceptual sub-phase,* which is characterized by primitive manipulations of symbols and the beginning of symbolic thinking, although the child is unable to translate sensorimotor actions into operations. That is, he does not intellectually transform objects of knowledge, but merely copies the reality he perceives. He learns by imitating models; he improves his language skills. The differences he observes between his own actions and his chosen models force accommodation; repetitions of activity in play and elsewhere lead to assimilation. The child is now consciously acted on by his social and physical world.

In these preoperational ante-school years, children do not understand causal relationships, because they have not yet created a systematic method of separating and testing variables. These children are able to change single variables and to correlate results, but they do not perceive interrelations between actions and results. On the other hand, the child of five or six can identify members of a class, and separate them from members of another class, but it is difficult for him to compare subclasses with the whole class. This is because he thinks that each subclass is as large as the entire class. To him, part is equal to the whole. His new symbolic lore, however, enables him to think more fluently. He is no longer limited to physical motion and its direct consequences: he can also extrapolate actions and consequences to the future and to the past.

A second sub-phase, the *intuitive sub-phase,* begins about four and extends to the age of seven or eight. The child extends his ability to classify and grasp, his insight into relationships, and his skill in numerical thinking. These capacities are *operations* in Piaget's terminology; they are concrete and non-symbolic, because they are actions on objects. The child, guided by an expectation arising from past assimilations, is frequently disappointed as he attempts to cope with his environment. If his mental structure is sufficiently discriminating to note these discrepancies, the child will be forced either to accommodate to the change, to assimilate it, or to retreat into some kind of emotion-charged failure. Children in the first years of this phase are not conservers, nor are they able to think reversibly. At the age of five and a half to six, children first begin to see contradictions in conservation of quantity. A six-year-old says that quantity decreases when a volume of liquid is poured into several glasses. This discrepancy between reality and his observations, if noted, may lead to conflict. These children think egocentrically, focusing on what *they* see or feel. For example, a box moves because the child pushes it, not because a force is exerted. Clouds move because the child moves or because the sun is pushing them.

About age seven to eight, children enter a third sub-phase, *mental-concrete operations*, in which they begin to connect actions with specific results. They internalize these actions and reactions, fusing them with other similar actions and reactions into sets of higher-level ideas whose predictive capacity is greater than that of their sub-concepts. The child comes to think objectively, evaluating and judging in less egocentric terms. His operations, which may be mental, are still restricted to concrete-empirical props and to direct experience. That is, he still visualizes and manipulates the objects he thinks about. He is able to identify variables and to work out the results of possible changes by direct manipulation, but he is not able to generalize them at the onset of this sub-phase. Conservation, classification, and serialization appear at about the age of seven to eight; this is the time when the child demonstrates that he can simultaneously hold two judgments in mind and compare them.

These children are unable to connect ideas, to visualize reciprocals and inverses, or to improve experimental efficiency by mentally changing one variable while holding the others constant. Instead, children must rely on direct manipulation or intuition. They are not logical thinkers who follow a chain of related ideas; although they group objects in simple classes, they cannot group classes or relationships into more comprehensive groups.

Once he has images evolved from operations with concrete objects and has verbalized concepts, the child has a new capacity for solving problems, both by trial and error and by mentally testing hypotheses. He can understand new ideas by associating them with pre-existing ideas. This logical operation is no longer concrete, because its raw materials are the images of objects which have been observed or handled. It is limiting, however, because of the excess imagery required, to cope with difficult problems. He cannot manipulate symbols *as* symbols, as, for example, in the gas law formula, $PV=k$, because these symbols are far removed from concrete referents. Thus, in problems of gas expansion or contraction, the child falls back on direct experience, or on intuition.

With increasing maturity, children are better able to deduce from the general properties of a class the properties of its individual members, without falling back on direct experience. That is, they are beginning to think in a formal, propositional way. They can reason from hypotheses and assumptions, and not merely from objects which are directly at hand. The adolescent can think of "propositions," that is, of the possible results of the actions of the causal variables which he hypothesizes. In other words, the adolescent *can* think of all relevant possibilities in a situation; the younger child must find them by testing variables, one after the other.

This capacity for abstract thought and for forming ideas about ideas comes earlier in the sciences than in many other areas of experience, because children encounter such concepts of science as weight, time, and space more frequently than concepts of government or family institutions. The importance of such encounters is well illustrated by the regression of children, adolescents, and adults who are confronted by situations which are new to them.[4]

The age levels which Piaget proposes are approximate, varying widely because of intellectual factors, experience, training, and socioeconomic status. It is obvious that children often operate on more than one level at more or less the same time, depending on the nature of the challenge. A child may, without self-contradiction, operate logically in one field and not in another, or operate inconsistently in the same field at different times.

Piaget argues that each stage arises only when its predecessor has been properly attained, and that if an early stage is incomplete, later stages will be defective.[5] He remarks that teachers should not directly correct a child's ideas, incorrect though they may be, but should instead provide a sufficient variety of experiences to enable the child to correct himself. In this way, he avoids an explanation (harmful accommodation) which is not in accord with his own thought.[6]

If children are to master the Piagetian operations of ordering objects and ideas in series, classifying them into related and non-related groups, reversing the steps of an operation, sorting out variables, discovering relations between variables, and dealing with reciprocal relationships, teachers should provide the many kinds of concrete activities from which these thought processes arise. For example, although inverse-square laws as mathematical propositions are probably meaningless to children, the foundation for understanding them can be laid by direct experience with magnets, static electricity, and light intensity.

The application of Piaget's comprehensive theory in the classroom must be left to the future, even though several of the new elementary-science curricula have implicitly or explicitly adopted some of his guiding conceptions, for Piaget's work is exceedingly difficult to translate into operational classroom terms. His is a theory of development, not of learning or of teaching. There is no way at present of identifying stages which can be accelerated by special training. Stendler remarks that "sixteen-year-old thinkers can never be made of six-year-olds, no matter how carefully the educational program is planned";[7] perhaps, however, eight-year-old thinkers can be made out of six-year-olds if this result is consciously sought.

Factors affecting cognitive growth

Individual differences

Every prospective teacher is introduced to the existence of individual differences in intelligence, aptitudes, and physique. Nevertheless, the enormous range of variation, even in infants, is apt to be ignored, despite its implications for our mass education. For example, the almost unbelievable differences from individual to individual in the gross structure of organs, the functioning of the endocrine and enzyme systems, the body metabolism, the activity of the nervous system, and the genetic apparatus is not sufficiently appreciated.[8]

We are not yet knowledgeable enough about the differences which exist between boys and girls in cognition. For instance, the extent to which these variations are genetic rather than environmental is unknown. Boys are more analytical in their thought patterns than are girls, despite the early superiority which girls manifest in language skills.[9] Girls tend to talk at an earlier age, to speak in sentences, and to learn to read more easily than boys. However, boys read as well as girls by the fifth or sixth grade, although girls are somewhat more fluent. They appear to be equally capable in elementary mathematics, although by adolescence, boys are superior in spatial tests and in analytical deductive thinking. Girls seem to think in more global and general terms, apparently influenced by the diversity of their environment to a greater extent than are boys.[10] Boys are said to be less rigid and more curious than girls in dealing with new phenomena and new ideas. Curiosity, a necessary element in fruitful investigative learning, is relevant because children who are curious either learn or retain more in a given time period than children who are relatively incurious.[11]

The influence of the cultural environment in these tentative generalizations must not be discounted. It may be that male curiosity and analytical power are related in some causal way to society's approval of male aggressiveness. Boys are encouraged to be independent, to have high aspirations, to go their own ways. Girls, on the other hand, are expected to be more passive, to respond to the needs and desires of others, and to help others at the expense of their own individuality.

The observation that underachievers and poor readers in school are much more likely to be boys is at least partly attributable to environmental factors. Girls tend to receive higher grades in elementary school classes, despite their failure to surpass boys in achievement on standardized tests.[12] The woman-dominated school room neither evokes nor encourages the kind of participation which boys associate with masculinity. School rewards are for conformity, "good" behavior, self-discipline, and cooperation—qualities which in themselves are not always compatible with the requirements of scientific investigation.

Teachers must make a special effort to adapt school work to the special interests and capacities of boys. And at the same time, they must encourage girls to be more independent and self-sufficient, to ask questions, and to reject implausible answers, if *their* scientific potential is to be fulfilled. Because boys seem to be somewhat better in analytical thinking, they should be given frequent opportunity to enhance this strength. And, concomitantly, the seeming deficiency in the ability of girls to think analytically is a strong argument for an even more intensive series of analytically oriented learning experiences. This, we believe, is a very strong argument for science learning through Inquiry.

In addition to these sex-linked differences, there are enormous variations between children in every phase of the mental spectrum. For example, no two children are equal in their ability to solve problems, to plan a course of action, to complete a specified sequence of activities, or even to respond to their teacher's stimulation and reinforcement. These differences must affect both the teaching and the learning process, and, for this reason, stereotyped instruction in science is inevitably an invitation to mediocrity. The wise teacher knows that no single instructional method, whether it is Inquiry, recitation, or programmed learning, is sufficient to sustain interest, to develop cognitive skill, and to maintain "the responsive environment" which nurtures learning.

The intellectual processes by which scientists have created modern science are unique in their fusion of concrete-empirical (direct) knowledge with inductive and deductive reasoning. This fusion of method and content should be one of the most important functions of elementary school science.

Activity

Students of young children stress their restlessness, ceaseless activity, and short attention span: these characteristics are particularly obvious in the restraining atmosphere of the classroom. The notion persists that this kind of perpetual motion distracts from the daily business of the classroom, and that if children would only sit still, the business of learning could proceed with dispatch. But this belief is a misconception, because the growth of logical thought is a function of activity, of experiencing, of handling and manipulating. Activity is not merely an expedient by which to arouse interest or to allow children to "prove" a statement in the textbook. On the contrary, in young children thought evolves from physical actions and not from the objects acted upon. The relationship between physical manipulation and growth in perception and image formation is well substantiated.[13]

Some of our traditional ideas about the differences in the activity needs of older children have been challenged by recent research. Teachers have often assumed that fifth-grade children are less likely to be challenged by abstract ideas than eight-grade children. Davis, however, describes fifth graders as "natural intellectuals" who enjoy abstract thinking, in contrast to seventh and eighth graders, who are more "practical." Seventh- and eighth-grade children want to explore, to build, to move around, and to take chances; these activities are fundamental in the modern science curriculum. First- and second-grade children learn through action, and educators may have seriously underestimated the dependence of older children on activity-based learning.[14] As a result, children in the junior high school years suffer because they are rarely "doers" in the science classroom. This premise is supported by Eaton's study of sixth-grade achievement in astronomy.[15] Eaton found that the majority of children learned astronomy best from a text which provided many different kinds of activities.

Perception

Young children are drastically circumscribed in what they perceive, even in a highly specific and restricted context. They remain unaware of environmental occurrences which are obvious to older children. As they mature, however, their awareness of their environment grows, partly because of the growth in mental imagery, a growth which comes from reading, and partly because of an extended interaction with their physical world. They become better able to plan ahead and to anticipate future happenings. As their thought pattern becomes more flexible and less egocentric, and as their cognitive structure grows, they are better prepared to interpret complex stimuli and to sort out the relevant from the irrelevant according to recognized and meaningful criteria.[16]

Young children usually require special training if they are to distinguish differences among the properties of objects, the relationships of these objects, and the individual objects themselves, interrelationships which comprise what has been called the "natural history of material objects."[17] First-grade children exposed to the University of California Science Curriculum Improvement Study unit on "Material Objects" were significantly better at identifying the similarities and differences among various forms of an object than were children who lacked this training.

In one lesson, children separated different kinds of unpainted wood samples according to such properties as grain, color, and aroma. After this sorting, the children were asked to count the number of different kinds of wood represented by their test specimens.

In a follow-up lesson, children sorted eleven different kinds of minerals, again according to their physical properties. Similar experiences with common objects such as buttons, nuts and washers, leaves, and metals provided the conceptual framework by which these children were enabled to gain significantly in perceptual and analytical skills.

Children with special training are better at observing experiments and describing what they see than are untrained children.[18] For example, in one of the Science Curriculum Improvement Study experiments, the experimenter filled a balloon with carbon dioxide generated by mixing vinegar with baking soda. Children with "Material Objects" training not only were more successful in describing what they had seen and in explaining why the balloon was inflated, but they were much more likely to conclude that the balloon was not filled with air.

Few first graders were able to devise an experiment to test the hypothesis that the inflated balloon was not filled with air. To this extent, they were unable to apply their observations and previous knowledge. As Thier remarks, "They are not able to put together a conceptual scheme for solving this problem."[19] The problem was probably too abstract for their level of cognitive ability. However, the experimenters did not try to cultivate skill in testing assumptions, nor did they provide the children with early related physical and conceptual experience, although attention to this particular goal would probably have resulted in significant growth. Despite the general and undiscriminating perception characteristic of the young child, the evidence derived from this and other studies shows that ability to sort out environmental stimuli can be measurably increased by suitable training.

As children mature, they tend to rely less and less on immediate perception as the main source of concepts and relationships, providing that their new experiences are closely related to previous learning. As they draw on their own growing experience to find clues by which assimilation and accommodation may take place, they become sensitive to new subtleties and environmental patterns. At the same time, they tend to fit what is seen into pre-existing patterns and biases. A contrary observation may be ignored, or isolated in some mental compartment, neither accepted nor rejected. Children may bend and distort what they see. For example, in one experiment, children insisted that objects of different mass fell at different velocities even though they were simultaneously released from the same height. Most children who predicted that the heavier of the two objects would strike the floor first were certain that it had. The desire to make their prediction come true was sufficient to distort perception.[20]

Children organize our complex world into their own individual explanatory patterns. Their hypotheses and intuitions often grow out of a vision which is not important to the teacher but is intensely vivid to them. Young children may clutch so tenaciously at the idea that big things sink, because this is what they see, that they ignore the existence of such variables as weight, volume, and the supporting liquid. Time, as well as both directed and incidental experience, is required before the complexity of nature becomes more than a figure of speech to them. This insight into physical existence can never be achieved by telling children that there is more to the world than what they themselves see.[21] This is why perceptual growth is inseparable from physical experience.

Symbolism

As the child grows, ability to manipulate abstract ideas also grows, because he continually adds to and enriches his store of symbols and abstract terms. He comes to think about wood as an entity—not a particular specimen, but rather an abstraction, with such characteristic properties as floating, slivering, showing grain, and being easily cut. As these ideas are integrated into his cognitive structure, they increase the power of that structure, because they are generalizable and predictive. But they also gain in power by being related to the child's general knowledge. As his vocabulary increases in size and precision, the number of relationships, distinctions, and refinements which he can generate in his thinking also increases. With sufficient practice in building relationships between the conventional concrete props of early learning, the learner becomes more skilled. As his ability to manipulate words and ideas grows, he begins to separate the relationships from the concrete objects with which he began.[22]

This idealized sketch reflects what should happen to most children and what probably does happen to them, yet it is quite apparent that children have often not mastered the words they use. They have perhaps never made the transition from the concrete to the abstract meanings of their vocabulary. The teacher should beware of emphasizing verbalistic response too much. Mere verbalism, repetition of phrases, sentences, and cliches, does not guarantee understanding at any level.

John Holt's comments about the children he taught are pertinent:[23]

> All she [Marjorie] knew was that she had been told to start doing something and didn't know what to do. She was wholly incapable of analyzing the instructions, finding out what part of them made sense and what did not, where her knowledge ended and her ignorance began.
>
> Children like Marjorie get in the habit of waiting for teachers to show them how to do everything, so that they may continue by a process of blind imitation; they never learn how to get information out of verbal instructions. In fact, they do not seem to believe that verbal instructions contain information. They do not expect to be able to figure out from mere words what it is that one wants them to do. Nor can they distinguish between the goal and the route needed to get there, the job to be done, and the method needed to do it. If someone gives them a problem, they either know or don't know "how to do it." If they don't the problem itself is meaningless to them.
>
> And this is the great danger of asking children to manipulate symbols whose concrete meanings they do not understand. After a while they come to feel, like Marjorie, that all symbols are meaningless. Our teaching is too full of words, and they come too soon.

The child's logic

Out of a tangle of sense impressions, the child picks certain related visions, which may be meaningless to an adult, but which make sense to him. The assortment of curios in the trouser pocket of a twelve-year-old boy, for example, is valuable to him. This collection of junk embodies associations, future uses, indeed, even wealth of a kind. To the adult (woman?) there is no logic in such a collection, but this is because the adult is applying (at least on this occasion) the formal logic of an exalted maturity.

Do children think in logical pathways recognizable to adults? To answer this question, let us examine the nature of cause-and-effect reasoning. If children do have an inherent capacity or ability for cause-and-effect thinking, it is obviously many-faceted and exceedingly complex. Many young children appear to think causally on occasion, whereas adolescents and adults sometimes react in characteristically childish ways. The large body of research in children's cause-and-effect thought patterns shows clearly that very young children often propose reasonable explanations, whereas older children may fail with the same problem. An interesting study of causal thinking was reported by Inbody, who asked fifty kindergarten children to answer a number of questions dealing with weather, buoyancy, and electricity. He grouped their answers into six categories:[24]

1. Generally correct and causal.
2. Plausible, causal, but incorrect.
3. Correct, but verbalistic.
4. Incorrect, non-causal: animistic, or anthropomorphic, or religious.
5. Descriptions or restatement of observations.
6. No explanation of any kind.

The order of frequency of response was 2, 4, 1, 5, 3, 6. All of the children proposed several different types of explanations, although most relied on just one or two. About one-quarter of the children gave explanations which were predominantly causal. Questions about freezing and wind, the phenomena with which children had the most experience, were most likely to be answered causally. With less common phenomena, causality was usually not invoked. To these children, for example, air in an inverted tumbler in water meant that "Nothing *kept* the water from entering the tumbler."[25] In their contact with non-empirical events or with indirect phenomena, some children confused cause and effect. Others resorted to animism or anthropomorphism, or appeared to think the phenomena were unique and without cause. Because of their limited experience, these children were unable to provide coherent explanations, nor could they detect contradictions which were apparent to older children. Explanation 3, "Correct, but verbalistic," meant that even though a scientific principle had been correctly stated, the child did not really understand it because he was unable to use it in a prediction.

Inbody concluded that the ability of children to make cause-and-effect statements depends on a rich experience with many aspects of a phenomenon, and that overgeneralizing and failure to note similarities between events is the result of inexperience with these events and unfamiliarity with causal thinking.[26]

The role of experience in causal thought is well illustrated by Mogar's finding that five- to six-year-olds who had an opportunity to play with floating objects, and to whom the comparative buoyancy or lack of buoyancy of large and small objects was pointed out, were able to explain floating as a function of size more effectively than children in control groups. (The experimenter was aware of the distortion caused by equating size with floating for the sake of simplicity.) The children clearly benefited by experience with floating objects in improving the quality of their causal thinking.[27]

Most of the recent work in children's causal thinking is contradictory to Piaget's conclusions, which are derived from his research during the late 1920's. Piaget hypothesized that young children explain natural events by combining free will on the part of objects with a "moral" attraction or repulsion between the object and the natural world. For example, he said that children think that rivers are attracted by lakes, rain attracts clouds, and rocks pull water to make it flow. At a later stage of development, they believe the attracting or repelling force arises from some kind of contact, but even then, an object in motion is still the positive cause of the action. The sun, for example, is forced to move by clouds, but it also forces the clouds to move with it. Eventually, these notions are replaced by the idea of purely mechanistic and non-living forces. At the age of five, children believe that *they* make the clouds move with them as they walk. At six, clouds move because God and men make them move. At about seven, children say that clouds move by themselves, but that this motion is caused by a mystic compulsion exerted by the sun or the moon. At eight, they believe that the wind makes clouds move, but that the wind is itself a product of the clouds. Not until the age of nine (approximately) is cloud movement correctly explained.[28]

Piaget quotes one seven-year-old child as answering the question "What makes the clouds move along?" by saying, "It's the sun... With its rays. It pushes the clouds."[29] Piaget believes that *physical* determinism begins to have meaning for the child when the notion of chance appears, at about seven to eight years of age. Prior to this age, the child attempts to eliminate chance factors. Because he thinks there is a reason for everything, he tries to explain what he sees in moral and animistic terms, whereas older children and adults explain many of these events as chance occurrences.[30] With chance, there arises the conception of physical law devoid of personal compulsion.

The domain of children's causality is exceedingly complex and confusing. There is agreement that the kinds of experience, the degree to which children are free to interact with their environment, to push and pull, to test, to handle, and to experiment are important factors in conditioning causal thinking. Only as children have the opportunity to deal with causality, to vary conditions, and to experience directly changes resulting from these variations do they learn to avoid the fallacy of thinking that that which occurs first is the cause. Here again one sees the importance of science instruction that permits children to encounter a wide variety of situations in a relatively unstructured setting.

Piaget also comments that the child of seven or eight does not reason inductively or deductively in adult fashion, but rather transductively, that is, from particular instance to particular instance. He does not generate general ideas from individual facts or ideas, nor does he make use of more general propositions to validate specific ideas. Instead, he moves from one individual item to another that is unrelated by logical necessity. The child of seven who insists that the sun is alive because it moves does not also think that all moving things are alive. He does not believe that all moving things live, because he knows that clouds, which are not alive, also move. The focus of reasoning in this child is on individual cases, without recognition of logical necessity.[31] Of course, children who say something is alive may mean only that it is active, moving, and do not necessarily impute feeling or purpose to it. Indeed, they may simply not know that not all things are alive.

Szeminska asserts that three causal stages may be observed in children:[32]

> I. Answers combining facts, concepts, or phenomena which are linked by their simultaneous occurrence or by physical proximity.
> II. Reference to the causal relation, but without comprehension of the passage from cause to effect.
> III. Complete explanations with comprehension of the necessary conditions and of the part played by the various factors which enter into the causal sequence.

Causal thinking in personal, non-school experiences grows more or less regularly in quality until, between the ages of fourteen and sixteen, it is predominantly stage III. The growth curve shows some gains after initial teaching in school, but the decrease which occurs in the following year leads Szeminska to conclude that "the acquisition of the knowledge was strictly mnemonic [by means of artificial memory aids]."[33] On the other hand, information which is more "pertinent" to the children and therefore more readily assimilated on an intellectual level is not only better remembered, but is better assimilated during the course of the next year.

Young children are severely handicapped in dealing with causal relationships, because they are unable to carry through a consecutive series of intellectual steps. In the operation of a pendulum, for example, they fail to separate out the length, the mass, the amplitude, and the material of the bob, and therefore cannot vary each in turn, holding the others constant. They do not think, "If I use the same bob and the same starting point on the swing, and if I make the string longer, then the changes I see in the number of swings in a minute must be because I made the string longer." The effect of teaching children to analyze problems in this way has not been the subject of much educational research, but the success of the new elementary science curricula which stress precisely this kind of process instruction in a framework of Inquiry is a most encouraging sign.

Certain causal relationships, particularly those in which multiple variables act, are difficult for children to handle. The selection of relevant factors is difficult even for adults with long experience in scientific endeavor, and the difficulties which children encounter are surely understandable. The young child can often grasp the significance of certain variables but fail to note the irrelevance of other variables. This too must come with experience.[34]

These and other difficulties were encountered by second and third grade children in a Piagetian experiment conducted by Ervin.[35] Their task was to predict and to explain the bending of a number of flexible rods under the action of four independent variables: (a) the composition of the rods, (b) length, (c) thickness, (d) weights attached to the ends of the rods. A few second-grade children and a larger number of third-grade children were consistently successful. Boys did better than girls in each grade, but there was no difference in IQ between those who succeeded and those who failed.

A number of children who were successful with one or two of the variables failed with others, but no particular order in this failure or success was discovered. Correct prediction with the first variable did not mean that the second would be correct, nor did failure with the first variable mean that the second would be incorrect. The experimenter assumed that failure would stimulate children (perhaps because of the ensuing dissonance) to reverse the direction of the chosen variable or to select other variables, but this did not always occur. Indeed, many children, including those who sometimes used controls, often worked with two or more variables at the same time (despite an injunction to the contrary), perhaps believing that they would see a greater change. These children may have been unwilling to risk short-term failure, and therefore incorrectly tried to increase their chances of success by changing two variables at a time.

However, when the children were asked to explain their failures, about half of their explanations cited one or more variables which had not been controlled. A number of the children knew that these variables existed and had referred to them in earlier explanations. It is probable, therefore, that the children were now focusing on a different aspect of the problem, or that these variables now seemed to be unimportant. Many of the new hypotheses proposed after initial failures properly took these variables into account.

Many children acted as if they believed that a variable which was effective in one case—for example, a small weight bending a thin rod—would always have the same effect; that is, the weight would bend a thick rod an equal amount. The children who worked with two variables at a time often justified disregarding instructions by remarking that they just wanted to see what would happen. They may indeed have been curious, but perhaps they were uncertain and desired to avoid committing themselves.

Children failed for a variety of reasons. Many were puzzled by word meanings. For example, some children equated *length* with *thickness* and therefore did not attempt to control length, or else they used *heavy* and *light* interchangeably when referring to the composition of the rods, their thickness, and the weights. Several children believed that the weight of the rod and the weight suspended from the rod were somehow connected. These verbal confusions are certainly not unexpected in children of this age.

The variables which children tested were frequently chosen because of their physical prominence instead of being systematically tested one after the other. Again, this is to be expected. Piaget suggests that it is not until early adolescence that this pattern of systematic testing becomes dominant in the majority of children. The children, in this experiment tended to repeat unsuccessful predictions and tests and to restrict their choice of hypotheses. Their most prevalent error was to disregard uncontrolled variables in their explanations.

It seems to be significant that when these children were confronted with novel predictive situations, their choice of variables depended more on verbal fluency in differentiating between variables and on the quality of earlier explanations and predictions than on the types of training situations.

Perhaps this only means that children (the successful second graders, for example) who already think analytically or who are moving toward analytical thinking will solve these multi-variate problems. On the other hand, even without instruction directed at improving the child's ability to solve these problems, many children were able to overcome errors and to achieve some degree of success. It is probable that a knowledgeable teacher could help children grow significantly in analytical thought by eliminating verbal misconceptions, by providing many opportunities for children to experiment individually and in small groups, and by working cooperatively with the children in assessing the results of their experimentation. Almy has pointed to the enrichment of primary-grade instruction that can be achieved by teachers who are thoroughly grounded in Piagetian insights and techniques.[36]

Concrete operations – causality[37]

Piaget remarks that the transition from concrete thought to formal logic begins when children first discover that much of what occurs in the world is a result of overlapping, independent factors. That is, a particular effect may have several causes, or a major variable may be obscured by several non-causal variables. The child is frustrated because he can no longer investigate each variable independently. In the concrete stage, he is unable to separate the variables by excluding or neutralizing them. For instance, he may satisfy himself that most metal rods are flexible, but many, of course, are not flexible. At other times, he may discover that despite a general lack of correspondence between the strength and physical size of a magnet, the two are sometimes related. The more vigorous his search for instances of one behavior correlating with another behavior, the greater the chance that he will encounter the many exceptions which exist, some because of experimental error and lack of information, others because of natural characteristics of real objects. Botany is an extreme example of a field of science in which exceptions to rule are commonplace and therefore compound confusion.

Children of nine or eight or younger can isolate some variables. These children, if they are anxious to find the effect of a variable, can try to verify by observing or by experimenting. However, they are merely separating these factors out; they are not excluding them. Such separation may occur by simple observation; that is, by noting what happens both when the factor is present and when it is not present, or by actively controlling it (e.g., lengthening or shortening a pendulum). Observation and experimentation are not excluding, in the sense that children do not mentally separate out the variables and foresee the result if each variable is removed. In those cases in which the variable cannot be physically separated, children come to a standstill. Children from the age of eleven, however, are able to think ahead and even in relatively complex situations to predict the probable results.

When two or more variables are acting, the concrete-level child changes each variable to see what it does, not to find its effect on another variable. He tests brass rods and aluminum rods to see how much they bend, but he does not compare a long brass rod against a short brass rod to isolate the effect of length in bending. The older child not only eliminates length, but manipulates brass rods without concerning himself with different materials, because he has already neutralized them.

Once he is able both to neutralize and to exclude a variable, not only to ascertain its effect but to learn what the function of the other variables is, he is well on the way to formal thought. At this stage, the child can generalize these operations to all combinations of the phenomenon in question. For instance, a long thin brass rod is more flexible than a short thin steel rod. Unless the child excludes the kind of metal, he cannot say that the bending is caused by the length of the rod or by the inherent capacity of the metal itself. Some concrete-level children solve this problem because they encounter a sufficient number of random occurrences to force on them the notion that sometimes the metal is causal, and at other times the length is causal. They do not simultaneously judge these two variables, because they are unaware of the possibility of coexistence. They move ahead, multiplying cases and confused data, and thus diminish the chance of finding relationships. The formal-level child, on the other hand, compensates for differences in each variable by holding them constant, meanwhile varying each of the others in turn. He is able to deal with possible combinations mentally, without direct resort to the objects, *once he has a sufficient stock of accurate images to guide his mental operations.*

Mental models

One reason for the difficulty which many young children encounter in formulating mechanistic explanations of scientific phenomena is their inability to fit what they see into a coherent, logical scientific structure of their own. That is, they do not have a sufficiently powerful series of mental relationships, or mental models which help to organize thought and to give meaning to perception. Piaget's famous experiments with concepts of volume reveal that children do not form a model of space as a continuum until they are eleven or twelve. "Space as a continuum" refers to the fact that the absolute quantity of space in a container is unchanged despite the volume of the objects located in it. Until children can visualize total volume and distinguish between the internal volume of the objects and the volume which the objects occupy, they are unable to judge volumes correctly when the arrangement of the various objects is changed, even though these children may be conservers of "interior volume." The recognition that the volume of the objects in the container is constant is a necessary but not a sufficient condition for success in complex volume judgments. The following protocol of Piaget's shows clearly how the young child fails:[38]

> Jaq [eight years, 2 months] realizes that the water level will rise on the immersion of the tower of 3 × 3 × 4 [composed of cubes of 1 cm. on a side]: "Now what will happen if I turn it over?—*The water will go down a bit, because the house is at the bottom now.* Well, will there be the same amount of room in the house itself if I put the bricks at the bottom? *Yes, There'll be the same amount of room.*—And that means it's the same for the water?—*No, that's not the same.*—Well, supposing I split the house into two parts, will there still be the same amount of room inside?—*Yes, there'll be just the same amount, but in two parts.*—And then there'll be the same amount of space left for the water, eh?—*No, that changes. There'll be less room. No, more.*"

This child knows that the blocks maintain their interior volume, but he asserts that the volume of water (which is complementary to the interior volume of the blocks) is not only not conserved, but that the exterior volume of the blocks is changeable. To him, the interior and exterior volumes of the blocks are not necessarily equal!

However, a child who is three years older responds as follows:[39]

> Dro [11 years]: "Supposing I take these bricks and put them up this way [the blocks are arranged in units of 3 × 3 × 4] into the water, what will happen to the water?—*It rises. It's just the same if you put your hand in the water. It takes up a lot of room and so the water rises.*—And when I put them in this way [3 × 1 × 12] are they going to take up the same amount of space in the water?—*No*—Why not? *Oh yes! I was wrong, it stays the same.*—What about the space taken by the water all round? Is that the same too?—*Of course.*—Well, supposing we spread the bricks around?—*It's still the same. They'll always take up the same amount of room.*"

The presence of a mental model by which volume changes are related to volume invariance is evident.

Little research in the function and development of mental models in elementary-science teaching has been attempted, despite its obvious relevance. In a most provocative study, Anderson selected 180 third- through sixth-grade children matched by age, intelligence, grade, and sex. The experimenter presented five demonstrations whose explanations were not known to the children but which could readily be explained by reference to an appropriate mental model. The phrase "mental model" was defined as "a theoretical form or structure which is hypothesized on the basis of observation of natural phenomena."[40] It is, in other words, a theory, a set of assumptions, and the conclusions which are derived from these assumptions. At the end of the demonstrations, the children were asked to create a model to explain what they saw.

The demonstrations were:

1. A mixture of alcohol and water occupies less space than the sum of their separate volumes.
2. Surface tension is present in water.
3. An appropriate increase in temperature causes ice to change to water.
4. An appropriate increase in temperature causes water to change to water vapor.
5. An increase in temperature causes [the volume of] water to expand.

One molecular model is all that is necessary to explain all the demonstrations except number one, for which a model of alcohol as a liquid is required. Children were asked to give answers to such questions as "What is water like so this happens?" in order to "force" explanations in terms of the structure of water.[41] Following the five demonstrations, a mechanical model of the first demonstration was given. A container filled with marbles was presented. After each child had satisfied himself that no more marbles could be added to it, the experimenter showed that small steel shot could pass through the spaces. The child was then asked why the shot could fit. Following a brief review of demonstration 1, he was asked if the marble and shot demonstration "gives you any idea about why alcohol and water take up less space when they are mixed together?"[42]

Excluding those demonstrations for which no explanation was forthcoming, three kinds of models were postulated:[43]

1. Atomistic, in which such words as "molecules, atoms, little pieces, particles, and cells" were used. Most children who gave this response thought that the liquid was only partially atomistic.
2. Non-atomistic, in which water was considered to be magnetic, or sticky, or in which air pressure was causative.
3. Magical and animistic, in which the liquid was partly alive, or acted as if it were living, or "it just vanishes."

Several of the eight atomistic models are given below:[44]

1. Particles are different sizes.
2. Particles hold together or attract each other, freeze together, or lock together.
3. Particles come together because of electrical attraction, magnetic attraction, gravitational attraction, or because they are sticky.
4. Heat makes particles move faster.

Ten percent of the children explained surface tension of water by a magnetic-particle model. At the third-grade level, 16 responses were atomistic, 33 non-atomistic, and 4 magical or animistic, and there were 169 non-explanations. At the fifth-grade level, there were 48 atomistic responses, 32 non-atomistic, 1 magical or animistic, and 139 cases of no explanation. At the sixth grade level, 74 explanations were atomistic, 32 were non-atomistic, 7 were magical or animistic, and 111 were non-explanations.

The number of atomistic models hypothesized increased considerably following the presentation of the sixth demonstration. Thirteen percent of the children gave atomistic explanations prior to it; 30 percent afterwards. Sixty-four percent could propose no explanation for demonstration 1 at first; only 40 percent had no explanation for demonstration 1 after the sixth demonstration. It is possible, however, that the intervening demonstrations were learning experiences which led to more atomistic explanations when coupled with demonstration 6.

Despite the limitations of the experiment, it is evident that many of the children, including some third graders, were able to construct mental models. This number increased rapidly with age and grade level, perhaps reflecting some classroom instruction in science. As one would expect, children of higher intelligence were more successful, and the consistency with which mental models were applied increased with age. Boys seemed to be somewhat superior, but this is an inference unsupported by solid evidence.

The formation of mental models is important in transfer of learning, because it makes possible the application of a consistent explanatory scheme to apparently unrelated phenomena. Until appropriate mental models are formed, children cannot understand the logical necessity of the phenomena they encounter. The kinds of models which children *can* formulate and the extent to which these models are more than mere verbalism are unknown at the present time. Keislar and McNeil's experiment with first-grade children in developing a kinetic-molecular model is a case in point.[45] It is difficult to decide from their experiment whether concepts of molecules, molecular motion, and molecular attractions have real meaning to children, or whether children have once again demonstrated their capacity to manipulate meaningless symbols. (See p. 86 for a more detailed treatment of this topic.)

Problem solving

The formulation of mental models surely has implications for solving problems in science by reasonable and analytical modes of thought. Without a cognitive structure to which to relate the various aspects of the problem, the problem is inevitably left to the vagaries of trial and error. For this reason, discovery or Inquiry teaching, teaching which hinges on the analysis and application of scientific knowledge to problem situations, can succeed only as the appropriate facts and theories are assimilated by children.

Much has been written about the ability of children to engage in problem solving. The psychological dimensions of problem solving have been outlined, but the important implications for science education are as yet somewhat vague and uncertain. What kinds of science experiences will promote in children a generalized ability to cope with problems which are not exactly like previously solved problems? The precise answer to this question is not known. Educators are still exploring the differences which children, at a particular age level or at different age levels, show in problem solving. Indeed, the time-honored debate as to whether problem solving is a constellation of specific skills or a generalized ability has not yet been solved.

Ausubel believes that the most important difference between the problem solving of children and of adults is in the complexity of the problems that are successfully handled.[46] Older children and adults, he contends, are merely more sophisticated; supported by much more experience, they are better at verbalizing and symbolizing. It is safe to say that older children are more aware of the problem, more systematic in tackling it, more perseverant, less stereotyped in approach, and better able to profit from past error. Younger children focus on only one part of the problem at a time; they are more easily frustrated, tend to stray beyond the limitations of the problem, and are less successful in generalizing to other situations. For them, the problem must be more directly connected with physical objects and concrete imagery. They are less competent at verbalizing a solution and at transferring it, whether verbalized or unverbalized.

Teachers of science need to know much more about how problem solving is affected by rigidity, impulsiveness, anxiety, and the effect of teacher warmth and receptiveness before they can reasonably and consistently incorporate it into their teaching. We know that some children hypothesize impulsively, accepting the first answer which comes to them. Others, slower and more thoughtful, are more likely to be correct the first time. These children may be better at inferential reasoning than more impulsive children; they read with fewer errors, and are sometimes thought of as "inhibited."[47] Some children may fear to guess and be wrong; others guess too freely:[48]

> How often we have seen our answer-grabbers get into trouble. The fact is that problems and answers are simply different ways of looking at a relationship, a structure, an order. A problem is a picture with a piece missing; the answer is the missing piece. The children who take time to see, and feel, and grip the problem, soon find that the answer is there. The ones who get in trouble are the ones who see a problem as an order to start running at top speed from a given starting point, in an unknown direction, to an unknown destination. They dash after the answer before they have considered the problem. What's their big hurry?

Problem solving, in the scientific sense, refers to some perplexity in the environment, some unexpected or different occurrence which must be explained. Problem solving is not amenable to hasty, time-pressured investigation. If the ability of children to think in critical, reflective, cognitively structured ways is to grow, they must be given sufficient time.

Above all, problem solving as a goal of science education will be achieved only as children experience a variety of different kinds of problems; from this variety the general disposition to apply tested strategies can arise. Although this general disposition is helpful, it must be flexible, because reliance on a particular method or procedure is self-limiting.

Children do not intuitively know how to go about solving a scientific problem, even if it seems to be as simple as finding the effect of temperature on the rate of evaporation of water. Their questions are too diffuse to elicit pertinent information, such as the number of objects in the system and their properties. The inconsistency of their questions and actions demonstrates that most children are unfamiliar with tactics and strategies for problem solving. Not only are they unaware that planning is essential for obtaining suitable information, they have no notion of what "suitable information" is. They disregard or fail to take into account many factors which may be pertinent, concentrating instead on one or two salient but not necessarily important aspects. With no idea of how to find out for themselves, they are forced to ask someone for answers, or to "experiment" aimlessly. In defense of these children, who are untutored in Inquiry, part of the difficulty may be that they are inexperienced in expressing, both to themselves and to their teachers, what it is they want to know or what they have found.

That these preinstructional fumblings are remediable has been demonstrated by J. Richard Suchman's work at the University of Illinois. Dr. Suchman devised an experimental Inquiry technique in the course of which children view motion picture films of such physical phenomena as the bending of a heated and cooled bimetallic blade. At the conclusion of the film, the children attempt to devise an explanatory scientific framework by asking the "proper" questions of the teacher. In explaining why the strip bends, children often assert that it has been heated. This answer is partly correct, but it is misleading because it assumes that causality is a simple one-to-one relationship and that the only change in the experiment was a temperature change. Even the incorrect "explanation" that the metal was softened by heat is not really an explanation, because it omits any association with an external set of conditions and a scientific theory. Such "explanations" are not true explanations. The bending must be shown to occur as the natural result of a certain set of conditions and principles.

Suchman endeavored to shift children's explanations from a linear, one-to-one sequence to a realization of the multi-dimensionality of causation, in which several conditions operate simultaneously. The correct explanation, for example, must include the difference in expansion of the two metals, which, held rigidly together, bend if one metal expands more than the other when heated. This expansion, in turn, is a consequence of molecular activity.[49]

Suchman described the chief characteristic of the experimental group as it appeared to him during the first stages:[50]

> To begin with, there was a marked lack of autonomy and productivity, stemming—we believe—from children's dependence upon authorities, teachers, parents and books, to shape their concepts. When given new data, or a situation in which such data were available, the children rarely organized what they had, rarely gathered more data, rarely raised and tested hypotheses or drew inferences. Instead they blocked completely, began to offer unsupported conclusions, or produced a string of stereotyped probes that led nowhere. Accustomed to having concepts explained to them in discussions, pictures, films, and textbooks, the children were unwilling or unable to plan and initiate action with the purpose of discovering new concepts for themselves—even when all the data necessary for such discovery were available on demand.

The inexperience in framing questions of the fifth-grade children with whom Suchman worked is clearly reflected in the following extract:[51]

> Examiner: What made it [the bimetallic blade] go up? I'm here to answer questions.
> Mark: Yes, I know. I can't think of any to ask.
> Examiner: I see. Think. Try.
> Mark: [Pause] Well, I can't think of any questions.
> Examiner: What is it you want to know? What would you want to know?
> Mark: Why it bended upwards.
> Examiner: What could you do to find out what things were necessary?
> Mark: Try it. Ask someone who knew.
> Examiner: Yes, you could ask someone that knew, but that would just be getting someone else to tell you, wouldn't it? I mean finding out for yourself.
> Mark: Just try different things.
> Examiner: What?
> Mark: Well, you could get the materials and things, and then try holding the thing at a different angle.
> Examiner: What do you think would happen?
> Mark: I don't know.
> Examiner: Can you ask me some questions to find out?
> Mark: No, I can't ask you any questions.
> Examiner: You're completely stumped? You have any ideas now for any rules at all that would explain it?
> Mark: No.
> Examiner: None at all. It's a complete mystery to you? No hunches? And no ideas as to what you could ask me to get some hunches?
> Mark: No.

Many children were distressed by the challenge. Some remained silent, unwilling to venture a guess. Others who "explained" avoided the Inquiry procedure entirely, whereas some asked the first question which came to mind. They were unable to conceive of a scheme or plan by which the problem could be studied systematically.

Their questions were vague, ambiguous, incapable of clarifying, eliminating, fixing precisely, or changing conditions. Most of the children regarded experimentation as merely a repetition of events, or some kind of manipulation under close scrutiny. None, prior to training, accepted the necessity for controls or for the systematic identification of the pertinent variables. Because they did not approach the problem with a general plan which included the recognition of the objects, conditions, and events of the demonstration, they failed either to note the variables or to specify conditions when the variables were identified. For example, when children asked, "Was the blade hot?" they did not specify *how* hot, at *what* stage in the experiment the blade was heated, or what part of the blade was heated.[52]

Hypothesizing

Suchman found that "even a very small amount of experience and training under less than ideal conditions can produce measurable improvements in the question-asking of sixth-grade children ... the technique [Inquiry Training] in its present form has a marked effect on the motivation, autonomy and question-asking fluency of children."[53]

The training, which was limited to one or two hours a week for twenty-four weeks, is suggested by the following protocol of a child who is beginning to gain some confidence in his own ability to frame questions. The child is asked to explain why a metal can that is partially filled with water, heated to the boiling point, and then sealed collapses when cooled:[54]

S: I know that because there wasn't any air in the can, so when you poured the water on it, it cooled off and it contracted. So it collapsed.
T: You have a theory about contracting?
S: Yes. The can contracts when you pour water on it.
T: How can you tell when the can contracts?
S: It gets smaller.
T: If you take this theory about contraction, can you carry out an experiment to see if this idea of contraction really explains—can you find out if the can did get smaller?
S: Did the can get smaller?
T: No. What are you going to do with your theory?
S: I don't know.
T: Are you going to keep it?
S: No.
T: Why?
S: Because it's not right.
T: How come?
S: Because you said so.
T: What do you mean, I said so?

S: When I asked you, did the can contract, you said, no.
T: Did I say that your theory was not right, though?
S: No.
T: Who did decide that your theory needed some looking at?
S: Me.
T: Do you see how you can come up with an explanation, and then you can gather some information, and then depending on the information, you can see if your theory checks with the facts, and keep your theory; if it doesn't, look for another.

The teacher is helping the child in these early stages of Inquiry to visualize what happened and to propose logical ways of testing his theory. In the course of this process, the child realizes that his mental model of contraction is contradicted by the facts. Therefore, he will have to propose another explanatory model.

Creativity

Creativity is one of the catchwords of contemporary education. With the realization that creativity is not the province of the arts alone, educators have seriously, if belatedly, begun to consider its educational implications. At the present time, its meaning has not been uniformly standardized. To some, creativity is merely a result of free activity, and something of which all children are capable—for example, painting, writing poetry and stories, or perhaps even constructing an unusual shape out of building blocks. Others believe that few children are creative. Perhaps creativity *is* fundamentally the same in all kinds of endeavor—in art as well as science. There is no certainty that creativity, however it is defined, can be taught. There are many questions about creativity which remain unanswered at present. Does creativity in art and music arise before creativity in science? Is it possible for a child to be creative in only *one* field? Are internal or external factors more important in generating and in releasing creative potential?

Torrance, a leading investigator in this field, defines creativity as:[55]

> The process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing elements, disharmonies . . . identifying the difficulty; searching for solutions, making guesses, or formulating hypotheses about the deficiencies; testing and retesting these hypotheses and finally modifying and retesting them; and finally communicating the results.

In itself, this statement appears to be another version of "the scientific method." Surely, creativity is not problem solving in another guise! As Torrance himself notes, the missing element in this definition is the presence of *novelty* in the result. The outcome of a creative act may be of value to the creator or to his society; it may force a change in the normal pattern of thought or behavior of the child. But these effects, while significant, are secondary to the element of novelty, even if it exists for the creator alone. There appears to be some general agreement that the creator must be highly motivated and capable of concentrating on a course of action to the exclusion of distracting influences. Torrance is undoubtedly correct in his insistence on sensing problems, and on formulating and looking at them in unorthodox ways.

Torrance found in one experiment that children who ranked high on his creativity tests not only proposed more hypotheses to explain how unfamiliar science toys worked, but generated more original ideas. When matched for intelligence, sex, race, and teacher, creative children in grades one through six "had reputations for having wild and fantastic ideas, produced drawings and other products judged to be original, and produced work characterized by humor, playfulness, relative lack of rigidity, and relaxation."[56]

Torrance found that he was able to stimulate primary grade children to think of new ideas by leading questions. He formulated eighteen questions, several of which are given below, in the experiment on improving science toys:

> What would happen if we made it larger?
> What could we add?
> What would happen if we gave it motion?
> What would happen if we changed the shape?

Children who were instructed in the use of these questions and admonished to think of "clever, interesting, and unusual ideas" were more successful than those who were told to think of as many things as possible. This second group, in turn, was more successful than children without training.

Creative children are substantially better able to cope with difficult, frustrating and open-ended tasks than are non-creative children. They enjoy the challenge, the aura of discovery, and the uncertainty which these problems pose. They dislike closed tasks which embody a more or less well defined path to their solution.[57] For creative children, Inquiry is a fitting challenge. For non-creative children, the challenge will be to the teacher. He must provide a responsive environment in which the curiosity of children about science and their willingness to study it will be equally fulfilled.

There is some evidence that children who are encouraged to propose new ideas tend to produce more novel ideas. When children are trained to think up new questions, to reword problems, and to propose their own ideas about these problems, they become better able to deal with "entirely new and different problems."[58]

J. P. Guilford has identified some twenty intellectual factors which he believes are of importance in scientific creativity.[59] E. Paul Torrance, working mainly with primary-grade children, lists seven factors whose effect on creative thought he believes has been demonstrated:[60]

1. *Ideational fluency*—the relative ease of proposing many ideas without regard to their quality.
2. *Spontaneous flexibility*—the generation of many different ideas and approaches to a problem.
3. *Originality*—the unusual, uncommon, novel responses to a problem.
4. *Curiosity (questioning)*—a positive response to the unknown elements of the environment.
5. *Causal hypothesizing*—the ability to devise cause-and-effect statements.
6. *Consequential hypothesizing*—the ability to conceive of the consequences of changing conditions.
7. *Constructiveness*—the ability to devise a more or less practical method of solving a problem.

Torrance concluded on somewhat limited evidence that the capacity of children to use these factors grows from the first to the third grades. Boys are superior by the third grade, although girls moved ahead rapidly in the fourth and fifth grades, a finding which is consonant with the facts of developmental psychology. The ability to formulate causal hypotheses developed slowly but consistently, without the regression which was observed in the other factors in the fourth grade. Hypotheses of consequence, on the other hand, appeared to be more unstable than causal hypothesizing. They began at an earlier age, and were more strongly affected by sex differences.[61]

Sex-linked stimuli strongly affected first-grade responses. Girls, for example, were more creative than boys with a toy nurse's kit; boys were better than girls with a fire truck. Little difference in performance was observed with a toy dog. In the second grade, boys began to be superior with the nurse's kit, and by the third grade, they were "clearly superior" with all three toys. Many of the boys, however, shunned the nurse's kit; others called it a doctor's kit, and with that fiction, became more productive.

In addition, manipulation was a significant factor in productivity. Boys consistently handled the toys more than the girls did, although not significantly so until the second grade. In contrast to the boys, the girls did not manipulate the toys more from grade to grade.

Intelligence and creativity

Although there is a correlation between high intelligence (as measured by IQ tests) and creativity, it is by no means high. Many very intelligent children are not creative. Torrance asserts that only a third of the upper 20 percent of children in IQ will score in the upper 20 percent on creativity tests. The 135 IQ, which is often used to identify gifted children, may be an excessively high cutoff, because creative children often score below 135.[62]

Wallach and Kogan have criticized conventional modes of creativity research for failing to differentiate sufficiently between intelligence and creativity.[63] Their analysis is almost conclusive proof that the different measures of creativity which have been employed are better correlated with intelligence than with each other. They also question the time pressure and the testing atmosphere which surround the application of these measures. In order to eliminate these variables, Wallach and Kogan designed an experiment in which the creativity evaluation of 151 fifth-grade children was conducted in a "gamelike, non-evaluative context." They devised ten creativity indicators which proved to be highly correlated with each other and almost uncorrelated with intelligence.

From their quantitative and clinical observations, they found that the children could be grouped into four broad categories:[64]

1. High creativity-high intelligence: These children can exercise within themselves both control and freedom, both adultlike and childlike kinds of behavior.
2. High creativity-low intelligence: These children are in angry conflict with themselves and with their school environment and are beset by feelings of unworthiness and inadequacy. In a stress-free context, however, they can blossom forth cognitively.
3. Low creativity-high intelligence: These children can be described as "addicted" to school achievement. Academic failure would be perceived by them as catastrophic, so that they must continually strive for academic excellence in order to avoid the possibility of pain.
4. Low creativity-low intelligence: Basically bewildered, these children engage in various defensive maneuvers ranging from useful adaptations such as intensive social activity to regressions such as passivity or psychosomatic symptoms.

Wallach and Kogan believe that the creative thinking of children, especially boys, is likely to be most effective when their emotional state is somewhere between unconscious anxiety and high overt anxiety:[65]

> Those psychological processes associated with creative functioning require, for their optimal operation, a context free from or minimally

> influenced by the stresses that arise from academic evaluation and a fear of the consequences of error. To further *this* kind of goal within education, then, is to fashion a learning and teaching environment that will permit children to minimize the bind produced by negative sanctions for error.

They support discovery instruction because it combines both divergent (creative) and convergent (accepted) modes of thinking, and "therefore such a method is of relevance for both creativity and intelligence."

One of their most intriguing observations is that these thought processes, which they discerned in fifth graders, must have begun prior to the fifth grade. If there *is* a point at which intelligence and creativity diverge sharply, perhaps at the time when formal classroom instruction becomes more intensive, there may be no better time to begin to "restore the intelligence-creativity" balance.[66]

The implications of this study for improving the cognitive processes of children in the sciences were unfortunately not explored in depth, even though Wallach and Kogan believe that the kind of thinking which fosters individual creativity in academic subjects is not normally encouraged in the classroom. It should be possible, however, to build on the new insights which they have provided in order to reconstruct creative thinking in elementary science.

Intuitive thought[67]

It has been said that when children propose intuitive solutions to problems, they think like creative scientists. But the differences between these two kinds of intuitive thought are immense. The vague, formless approach of children is tied to concrete-empirical evidence. Their inability to use abstract symbols, coupled with a massive unsophistication and ignorance of general and specific knowledge, is hardly comparable to the expertise of scientists, who, in full cognitive maturity, bring their deep knowledge and general familiarity to new problems in their field. Despite an initial lack of system and precision, scientists are usually able to deal with new problems on a highly formal and propositional level. This does not necessarily mean that they approach these problems in a creative way, although a solution is more likely to be creative. They still may not succeed in solving the problem, even though they are so much better prepared than the layman.

On the other hand, children who propose intuitive answers may not necessarily be creative. Their answers may be both wrong and illogical. Ausubel believes that a child who is creative in some general sense thinks intuitively and creatively without possessing the tools for rigorous thinking. His answers, although incorrect, will be plausible. The intuitive child who lacks the perspective of factual and methodological knowledge must resort to guessing. If he is creative as well as intuitive, he will add the elements of originality and plausibility.

Some children are much better than others at proposing significant hypotheses and at testing and deciding whether to reject them. These are surely both creative and intuitive behaviors. There is no doubt that the intuitional capacity of many children grows with age, presumably because the children are also growing in knowledge and in ability to think in general terms, to use symbols in testing hypotheses. Even so, a cognitively mature adult, confronted with a problem in a branch of knowledge of which he is ignorant, is also forced to attack the problem intuitively. Because he can call on those elements of his previous knowledge which are transferable, and can manipulate this knowledge on an abstract-symbolic level, he is able to shorten the time required for the solution. He has already mastered a style of Inquiry and general techniques of gathering and evaluating the necessary information. Great scientists such as Harold Urey, Linus Pauling, and George Gamow have achieved great success in more than one scientific field because of this cognitive maturity. It should be added that these men are probably not representative of the great body of scientists.

In the classroom, the teacher must face the problem of balancing intuition-creativity, where it exists, with the developmental stages of her children. Unsupported intuition is likely to lead to error. Unless intuitive ideas are subject to testing, little is gained by their proposal. Therefore, the teacher should frequently confront her class with problems which can lead to verifiable solutions. Guided discovery is important in preventing the loss of class time in fruitless search. Verifiable information is vital; hypotheses are worthless unless they can by checked. (Of course, classroom limitations may preclude experimental testing, and therefore verification must come from other sources.) The teacher should encourage unorthodox approaches, but whenever possible, they must be directly testable.

The desire to learn

Children's interests in science have frequently been investigated during the course of the past half century. Almost invariably, the range and intensity of interests was determined by collecting from children lists of things they wanted to know about or questions to which they sought answers. But the general conclusions of the different investigators are invalid and unreliable guides for classroom action, not only because of the numerous contradictions in the ranking of interests, but because these interests change rapidly. A more important type of research than the classification and ranking of interests is still virtually unreported in science education—an analysis of the function of interest in making science teaching more effective. Is interest essential for motivation? Without a guiding theory of "classroom interest," each teacher must rely on her own intuition in devising challenges to which her children will respond.

Motivation in many classrooms is extrinsic, originating in some kind of reward from the teacher and classmates. Such shallow motivation is an unsatisfactory medium for encouraging independent learning. Undoubtedly, the direction of post-school life is often strongly influenced by desire for promotion or increased salary, or the desire to win the esteem of one's fellows or to serve humanity. These extrinsic stimuli, however, are insufficient to influence many adults to continue to be interested in science. Despite the fact that few will pursue scientific careers, there is hope that adults will become "scientifically literate" if they continue to read and understand science. If they are apathetic or hostile to science because they were bored or repelled by inferior science teaching, they will achieve neither autonomous learning nor scientific literacy.

Children themselves are the responsible agents for active learning. Children, not teachers, must ask more questions. Instead of an endless one-way stream of questions whose purpose is but dimly perceived by the children, the search for answers must begin with the learners. What depth of meaning can children extract from statements which are submissively accepted but never truly grasped? To talk about atoms without eventually putting them into a framework by which understanding is enhanced is to waste time. In Holt's words:[68]

> Children cannot learn much from cookbooks, even the best cookbooks. A child learns, at any moment, not by using the procedure that seems best to us, but the one that seems best to *him*; by fitting into his structure of ideas and relationships, his mental model of reality, not the piece we think comes next, but the one he thinks comes next. This is hard for teachers to learn, and hardest of all for the skillful and articulate, the kind we often called 'gifted'. The more aware we are of the structural nature of our own ideas, the more we are tempted to try to transplant this structure whole into the minds of children. But it cannot be done. They must do this structuring and building for themselves. I may see that fact A and fact B are connected by the relationship C, but I can't make this connection for a child by talking about it. He may remember the facts and what I said about the relationships between them, but he is very likely to turn my words into three facts, A, B, and C, none of them connected to any other.

Once past the elementary-school years, it will take educational surgery of the highest order to cut away formalistic and hardened learning attitudes and to replace them with more desirable principles of action. The evidence is indisputable that in the first few years schools can establish (or confirm if previously formed) a disposition for intellectual activities. Children who have not demonstrated a drive for intellectual mastery by the age of eleven or twelve are not likely to change even if confronted by excellent high school instruction. It has even been suggested that the most important intellectual contribution of the kindergarten is in the arousal of interest, desire, and enjoyment in learning, rather than in actual formal thinking.[69]

Factors that affect the desire to learn[70]

Despite the maze of environmental, personality, and intellectual interrelationships which every child exhibits, psychologists have been able to isolate some of the factors which affect learning motivation. The list given below, although not complete, is a helpful guide to the psychology of learning motivation:

1. *The desire to be accepted and respected by parents and other adults.* Although adult acceptance is more effective with young children and with girls, it is a relatively weak, extrinsic force. Peer acceptance is stronger, but more likely to be negative. Its effect is to reduce the importance of a task to the child; it is important not because of what it can do for him, but because it is important to others.

2. *The desire to be different.* The child not only seeks group acceptance, he searches for ways in which to be different from his friends. The desire to be different is a self-labeling device which provides unique identification. Children who are intellectually strong may choose the path of intellectual achievement, which, although rewarded by adults, is likely to isolate them from other children. This striving for uniqueness, no matter what effect it has on personal relationships, is characteristic of creative adults.

3. *The desire to emulate an admired model.* The child who, for whatever reason, admires a child or adult who is intellectually directed may try to be as much like him as possible. By emulation, he may attempt to maximize the possibility of achievement. The absence of an intellectual exemplar at home is thought to be one of the causes for lack of intellectual drive; most parents are not opposed to intellectual striving, but because they have not followed this pathway to success, the likelihood that their children will want it is diminished. "Do what I say, not what I do" is a parental exhortation doomed to be ignored. For this reason, teachers must be worthy of emulation even in the daily routine of the classroom.

The antithetical forces of differentiation and emulation appear to be strong in children. Human beings tend to separate themselves from groups which have little to offer them, and to identify with more potent groups. "Psychological development has a spiral form in which a child identifies with a group commanding desirable goals and, after maximizing similarity to that group, differentiates from it and passes on to the next identification, in an almost neverending seesaw struggle between maximizing similarity to one model and differentiating from another."[71]

4. *Anticipation of failure or success.* Very early in the child's school career, he begins to anticipate failure or success. The probability of failure is often sufficient to discourage the child from pursuing his school tasks and to force him to withdraw into himself. Very young children know, or think they know, what they can do, and they try to avoid the anxiety of failure or of competitive pressure to succeed. The strongest extrinsic motivations of the school sometimes accentuate withdrawal, because they increase pressure.

5. *Anxiety arising from learning conflict.* Depending on the child, overcompetitiveness, passivity, or sex-role conflict may affect his learning. Classrooms are typically competitive, each child vying with his fellows. Girls in particular may develop feelings of guilt, becoming anxious and inhibited and performing at a lower level; in the primary grades, boys have already begun to identify with men and to resist the passivity which is expected of them by their female teachers.

Many school subjects are sex-linked in that they are thought to be more appropriate for one or the other sex. The physical sciences and mathematics are "male-centered," and therefore girls are less likely to want to study them. The girl who is unsuccessful in physical science is not disgraced. Indeed, success in science may be defeminizing in the eyes of adolescent girls.

In the early school years, girls are much more successful than boys in school tasks, a difference which decreases as the children grow older. By adolescence, boys tend to be superior in mathematical and physical tasks, and certainly not inferior in their ability to read. It may be that young boys consider reading and arithmetic to be a part of the female-centered environment which they resist. Not until they are ten or eleven do they see the relevance between what is done in school and future vocation. This, coupled with minimal competitive anxiety, may help to explain the change in learning behavior. While girls are anxious to gain approval from their teachers, boys come to regard mastering a task as a symbol of their own ability.

6. *Work standards.* In general, children soon set standards of achievement for themselves which maximize security and minimize anxiety. Although children who are intensely competitive and desire strongly

to achieve may set impossible standards for themselves, those who are able but less intensely motivated settle for a median position in the class. The authoritarian teacher who demands high levels of achievement is not likely to stimulate children to change their work standards voluntarily. On the other hand, the teacher who through personal warmth and interest encourages children to raise their own standards of achievement is minimizing the tension which arises from the opposite pulls of security and adult standards.

7. *Attention.* Learning is rarely both easy and enjoyable. The teacher must maintain the attention of the class, even of those who are neither able nor intellectually ready. Unless the eyes, ears, and mind of each child are open, nothing will be accomplished. Attention is not captured by the teacher's stern admonition to pay attention, for children have learned to present an attentive facade without interrupting their own more interesting daydreaming. For this reason, the novelty of science activities and the genuine appeal of experimentation, which cut through this facade, are important teaching assets.

8. *Curriculum structure.* Gagné suggests that interest comes from success with a suitably structured curriculum. Children learn science because they like it. They like it because they are able to formulate new ideas out of what they have learned before. According to Gagné, sequence is important, because new learning and strong motivation arise from the "proper" presentation and sequence of ideas. Prior knowledge must be restructured in a variety of contexts and experienced in new and different ways if genuine integration of experience is to occur. Gagné believes that "content" and its "order" are the two most important factors in learning, and that both must be appropriate for the learner.[72] It is reasonable to assume that a child will want to learn if he knows exactly what he will be able to do when each task has been completed. Compare, for example, the motivational force of the statement "We will now study magnets" with its functional counterpart, "Learning the principles of magnetic action will enable us to understand how electric motors work, how doorbells operate, and how a compass indicates direction."

One of the strengths of science discovery is that it shifts the burden of motivation from the teacher to the student. In a problem-centered, non-authoritarian environment, cognitive motivation will be sustained as long as solutions can be found. This motivation is two-fold: (1) to solve the problem, to match what is observed with what is known or can be found; (2) to continue to experience in a free situation the pleasure and excitement of manipulating, of obtaining data, and to discover the power of reason and experimental design in finding answers.[73] This is the motivation which comes from successful strategies. Success in

Inquiry is thus capable of providing a self-renewing desire to continue learning.

9. *Curiosity.* Curiosity, inquisitiveness, and interest are strong motives, but they are erratic and unsystematic, easily satisfied and incapable of providing informative feedback. Teachers of primary-grade children are fortunate in that their children have not yet learned to camouflage their interest and quick responses. For them, the feedback is instantaneous, and curiosity quickly aroused (and perhaps as quickly lost). Their questions, comments, and attentiveness (or its lack) are direct indicators of instructional quality. This lively curiosity of children is obscured by the "show me" attitude of older children, who almost seem to challenge teachers to interest them.

The notion that science activities should only satisfy the needs that are revealed by children's questions is without merit, except in the hands of a great teacher. Questions do not necessarily indicate interests or needs. Indeed, questions may serve only to gain attention, to confirm fixed ideas or to remove fears, instead of providing intellectual probes.

Prior to entering school, the child is relatively free to make his own decisions, to build his own concept systems, and to do whatever he wants to do when he wants to do it. In school, however, he is no longer autonomous. He is under pressure to accept a program of learning into which neither he nor any other child quite fits. His interests are not the teacher's; the direction of class activity, even if *his* questions are welcomed, may be contrary to what he wants. Interests and curiosity are dissipated by teacher-originated tasks whose purposes are unknown to the child. The reasonable compromise by which the child is permitted some freedom to propose his own procedures and to decide the basis for accepting or rejecting answers is not always permitted, even though the challenge of this kind of freedom is sometimes sufficient to motivate learning.

Whether active or latent, the capacity of a child for intellectual endeavor is not necessarily a motivational force. Not until he realizes that he can do something which he thinks is desirable by hard, careful thinking will he transform potentiality into reality. For this and other reasons, it is important to provide a rich classroom experience through which potential interest is transformed into actual interest.

The nature of children's interest in science

Most of the interest studies in elementary science education confirm the deep interest of children in science, physical as well as biological.[74] For example, in one study of the "sharing periods" of 1,860 children in thirty-four communities and fourteen states, the category of nature and science was referred to most often, making up 25.9 percent of all "sharing" topics. Such topics as plants and animals (pets), space and astronomy, geology and weather, and chemistry and energy were included. The investigator remarked that children, as might be expected, were most interested in aspects of the environment which they could experience directly.[75]

On the other hand, Jersild and Tasch contend that children do not often ask questions about nature and science, and that these questions are less common than questions about reading, spelling, and the language arts. They state that not until the ages of twelve to fifteen are as many as 10 percent of children's questions about nature and science.[76] This is one of the few studies which rejects the general conclusion that elementary school children are interested in science.

Interest-centered instruction is often difficult to manage in the classroom. Probing, insightful questions are sometimes impossible to pursue because their answers may require resources and knowledge which are either unavailable or are too difficult for the children to understand. Interests may disappear in the course of instruction, or they may be so divergent that science becomes incidental and accidental. New ideas may cause some children to suppress curiosity because of an imagined threat to their security. Children may not care to show that they are knowledgeable about a topic which arises in class because they are reluctant to participate actively in discussion. Indeed, Friedlander derogates the importance of interest as a drive to mastery, and he insists that teachers continue to rely on extrinsic rewards, rather than on an innate and somewhat nebulous motivation in the child.[77]

Questions of why[78]

Children as young as three or four believe that matter behaves according to certain rules. This is their working model for coping with their world. When an unexpected or startling event occurs, a "cognitive dissonance" in Festinger's terms, the child's conceptual scheme may be unable to accommodate it because of his unfamiliarity with the situation or lack of perception, or because of the sheer complexity of the event. The child's scheme is almost always too fragmentary to reduce the dissonance which he experiences, and he turns to adults for help. He asks "Why?" because his own resources are insufficient to make sense out of what happened. (It may be, as some psychologists argue, that there is an innate drive for competence and a desire to know. How this differs from the drive to reduce dissonance is not clear.)

Children's "why" questions tend to become less frequent as they grow older, in part because children fill in some of the gaps in their mental models with sufficient information to reconcile what they see and in part because what they do in school is unrelated to what they themselves want. "Why" questions disappear because they are smothered by an unresponsive environment in which effective stimuli and effective answers are infrequent and adults are disinterested and impatient. These questions, with their potential for active, dynamic interests, shrivel away when they are answered quickly in order to satisfy the child's immediate need. Adults and teachers must be understanding, patient, and resourceful, responding to questions in ways which encourage the child's own exploration of his universe. Children want to know what makes things happen. They will not formulate sharp, clearly focused questions unless they are convinced that it is necessary for them to do so. The pioneering studies of Suchman show clearly that children can learn to ask this kind of question.

Children's "why" questions may be categorized as either information seeking or explanation seeking.

Informational questions

Whys of purpose. These are teleological or motivational questions, whose intent is to find out the purpose of an event—what it accomplishes or what role it plays. For example, "Why is thunder so loud?" may not be a demand for a physical explanation but simply a question of motives.

Whys of justification. These questions seek the logical necessity for rules, customs, and modes of procedure. Their answers come from definitions and axiomatic postulates. "Why is this an oak leaf?" and "Why is iron an element?" are examples. Questions for justification tend to be relatively rare in the sciences, perhaps because children have never been told that the foundation of knowledge is definitional and axiomatic.

Explanatory questions

Whys of causation. These questions probe the particular circumstances or relationships resulting in the event (e.g., "What makes lightning?" "Why do the rivers run down to the sea?"). The child may really wish to know the reasons for the contradictions he observes, or the chain of circumstances which inevitably results in the occurrence. He is seeking a certain kind of information. He is not looking for an animistic-moral set of rules, but rather for a genuine mechanical causality—even though his own conception of causality is confused and confusing. As children grow older, they learn to refine and to narrow these questions to such specifics as "What makes this happen?" "What causes it?"

The child, puzzled by the jar to his mental equilibrium caused by the discrepancy between expectation and experience, turns to an adult for help. Isaacs suggests that the distinguishing characteristic of these questions is their implicit "whereas" clause.[79] The first time a child encounters silicone putty, he may ask, "Why does this putty bounce... [whereas] clay doesn't?" An incorrect answer—for example, that it contains rubber—may eliminate this discrepancy. The adult sees no discrepancy. He may answer that even though the silicone putty looks like clay and behaves like rubber, it is made of other materials, and behaves in an unusual way. Or he may merely pass off the question.

Enjoyment

School science *can* be a deadly bore to both children and teacher if it functions only to communicate information. It is difficult to see how the motive of competence or the need for self-fulfillment through achievement will maintain interest in recitation-science. It may seem naive to insist that science can be fun, but it *can* be fun, and it should be. Science should be enjoyable not only because so much of it is directly apprehendable to children, but because children like to manipulate and to experiment. There may even be a "manipulative" drive which experience in science can satisfy. In a sense, science is "toy-play."

Discovery approaches to science instruction are exciting from a motivational point of view, because they begin with a conceptual dissonance. Children strive to eliminate this dissonance by fitting it into a dissonance-reducing framework. Even though this framework is incorrect, it may be perfectly acceptable to the child, and perhaps the best one which can be proposed at the time. But to think that an electric bulb lights because electricity is flowing through the bulb like water flowing through a faucet may lead him to think that he really understands. This erroneous model, even if it is convenient, must eventually be transformed into a more accurate and fruitful conception. The resolution of these difficulties will result in pride of accomplishment as the child successfully measures himself against the task, but guidance is essential: no child by himself can discover the laws of electromagnetic induction or invent the theory of evolution.

Surprise, doubt, perplexity, bafflement, and contradiction stimulate motivation. This assertion is in harmony with the principle of cognitive dissonance, providing that the challenge and the children are matched. If the challenge is too great, frustration inevitably occurs. If the challenge is too easy, the task is less fruitful. When the match is close, the child will be pleasurably and positively stimulated. Therefore, teachers should endeavor to create situations of expectancy which can soon be resolved. This may be accomplished by beginning with a demonstration or experiment whose outcome is puzzling or surprising. The wise science teacher knows how essential the element of surprise is in his teaching. The simpler the demonstration, the more vivid its effects. For example, allow a child to touch a rubber band at room temperature to his lips to note its temperature. Next, instruct him to stretch the band quickly, to touch it to his lips again, then to release it, and test its temperature a third time. The unexpectedly dramatic changes in temperature set the stage for an inquiry into the laws of conservation of energy.

Not all of science can or should be taught in this way, but it is surprising how many novel (to the children) and interest arousing science experiences call for the simplest of materials. Children, at least the younger ones, are naturally interested in exploring and in learning why. Even such seemingly trivial tasks as finding likenesses and differences, measuring, and counting can be happy experiences as long as they are not busy work.

Rich experience

Many psychologists are now convinced that intellectual growth of children is quickened by providing many different opportunities for exploring and experiencing their environment. Indeed, they believe that many of the learning problems which confront children from lower socioeconomic groups begin in the lack of cognitive stimuli in their home environment. The child changes because of maturation and learning, but his learning environment must change even more. Matching the child with the right classroom experiences is difficult, not only because of the physical limitations of the classroom, but because no two children are at exactly the same psychological stage.[80]

Finer discrimination of environmental stimuli, from gross perception to structural and functional classification, is an outcome of extended experience.[81] Unfortunately, this kind of exposure in depth takes more time than the average classroom has given in the past. Abstract ideas and relationships come only from a good supply of mental images, which begin to form as young children imitate desirable models in their symbolic play.[82] Concrete-empirical experiences, such as touching, smelling, tasting, lifting, throwing, weighing, bending, and twisting objects, help create the visual imagery necessary for the abstract, symbolic thought which gradually replaces its more primitive and less efficient forerunners.

Children in the early years of elementary school, in what Piaget calls the "concrete" phase, should have the opportunity to handle the widest variety of materials and to carry out a broad range of activities. These children are able to classify, count, and serialize reversibly. They must begin with concrete materials because of their limited abstract vocabulary and imagery, but it is from experiences with these materials that such concepts as causality, probability, invariance, and conservation arise.

Up to the age of four, which is the Piaget "preconceptual" stage, children think transductively, going from individual event to individual event. They focus on chance factors or salient features to the exclusion of important, although perceptually less obvious, factors. They reason that an object sinks because it is big, but a small pebble is heavier than a large cork because it is stone. Big does not denote a class of objects. Because big stones exist, little stones are also described as big, and are therefore heavy.[83] Only after many incorrect inductions, questions, and experience does image match reality. Indeed, it is not at all uncommon for even adults to respond transductively to new experience. They reason that because X is like Y in some one respect, it must be like Y in all respects.[84]

It has been suggested that the rate at which the child moves through the various stages of development is, to some extent, a function of the richness of his environment. Although based primarily on animal studies, this is a provocative hypothesis. Even if a child from an impoverished environment can think at an appropriate level of abstraction, his patterns of thought will be too limited because he has not had sufficient experience with related problems to develop successful strategies.

Hunt maintains that "the more new things an infant has seen and the more new things he has heard, the more new things he is interested in seeing and hearing; and the more variation in reality he has coped with, the greater is his capacity for coping."[85] (This does not mean merely play, for play eventually becomes boring, and, in any case, provides fragmentary learning experience.) There must be a reorganization of curriculum and method to challenge the child's capacity to reorganize and formalize experience.[86] Structure, the relationship of the facts and events of the learner's world, is created from a large store of facts by means of the capacity to reorganize these facts. Certainly, experience alone, whether gained in experimentation, teacher demonstration, or by observation and reading, is insufficient for cognitive growth. The child must react with it, transform it, think about it, deal with it, and interact with it.[87]

Children are not ready for the direct teaching of the structure of scientific knowledge. They must discover it or create it for themselves. Direct transmission of a body of knowledge and its unifying principles results only in verbal learning, and blocks the child from his own meaningful synthesis. As Piaget says:[88]

> Good pedagogy must involve presenting the child with situations in which he himself experiments, in the broadest sense of that term—trying things out to see what happens, manipulating things, manipulating symbols, posing questions, and seeking his own answers, reconciling what he finds one time with what he finds at another, comparing his findings with those of other children.

This is a functional definition of the Inquiry methodology.

It has been suggested that one way to help children build suitable strategies for reorganizing their experience is with exercises in classifying, serializing, comparing, and finding likenesses and differences. For example, Heathers suggests that children be given the opportunity to classify objects and events according to this scheme:[89]

1. Size, color, shape.
2. Degree to which they possess certain characteristics.
3. Likeness and difference.
4. Changing characteristics.
5. Changing relationships, distance, aging, growth.
6. Motion, direction, velocity.
7. Cause and effect changes.

The American Association for the Advancement of Science curriculum, described in Chapter 6, incorporates a number of similar exercises for primary-level children.

These experiences should provide practice in generalizing and in transferring to new situations the ideas and skills derived from measuring sizes, weights, shapes, and temperatures in as many ways as possible. Even if it is impossible to accelerate the growth of reasoning ability in young children (the evidence is not sufficient at the present time to decide whether or not acceleration is possible), teaching which is directed at this end will help children to learn much about their world.[90] Both school and home must somehow provide the interactions which stimulate each child to use his mental repertoire and to develop new and more inclusive patterns of intellectual operation.

If it is true that children of high mental ability, as measured by IQ, tend to come from higher socioeconomic levels and from urban and suburban centers, it is at least partly the result of their cultural and motivational environment. On the other hand, a child of high ability in a less-favored family or locality may have the benefit of special interest and ambition in his family, a stimulating home environment, or appropriate models to emulate.[91]

Socialization

One of the goals of the modern elementary school is to encourage children to work and learn cooperatively, because many decisions in our society must be made through consensus and mutual assent, and because individuals must learn to live harmoniously with others. Group learning also fosters intellectual growth. In working with other children and with adults, the child encounters other points of view, which help him restructure his own ideas and lead to a critical pattern, to a different way of looking at his environment. The young child is unable to conceive of an outlook different from his own. The knowledge that other children see things differently helps the child to "accommodate," to rebuild his own idea structure, and thus to approximate ever more closely a coherent operational scheme.[92]

Davis has commented on the fact that the children with whom he worked in his studies of the "new mathematics" were relatively unsuccessful when alone or in very small groups. He attributes their difficulties to the lack of communication of ideas and criticism and to the loss of that reinforcement which comes from showing "the whole class how clever you are."[93] Whatever the merits of such motivation, it is reasonable to expect that sharing and cooperative evaluation will enhance learning of facts and ideas which are not already predigested and completely organized.

Rigidity[94]

One of the desirable outcomes of science instruction is a willingness to examine different approaches to problems. Sooner or later, the child will encounter situations which are so different that established approaches either fail or are too time-consuming. The tendency to face new situations without changing one's responses, even if these responses are unadaptive, is called *rigidity*. Psychologists do not agree about the extent to which rigidity is a generalized personality trait. The kinds of situations involved are obviously influential, but the nature of the change in responses seems to depend somewhat on the child's generalized adaptive capacity. Despite extensive research on rigidity, the relationship between adaptive capacity and learning is still conjectural.

Children who are unable to tolerate ambiguity, which is a conflict between alternatives, also show a kind of rigidity; yet in science the evidence is often insufficient for either accepting or rejecting one of a number of conflicting hypotheses. In the year 1550, for example, the Copernican and Ptolemaic hypotheses explained the known data of planetary motion equally well, and it was not until late in the seventeenth century that the Copernican hypothesis was generally accepted. Inquiry is a study of problems, and problems, by their nature, lead to uncertainty. Children may become more rigid, more inclined to follow "tested" rules, if they are faced with situations which increase ego-involvement and personal anxiety. There is security in retracing familiar paths, yet the more difficult and ambiguous the problem, the less likely it is that the usual formulas will work. Some children who are forced to predict become more rigid, both in perception and in action, because they somehow feel threatened. For this reason, they unconsciously narrow or distort what they see.[95] This is not at all surprising—scientists of high reputation have been known to overlook or to minimize evidence which contradicts prized hypotheses.

Children who tend to think or act in fixed patterns are often seeking to avoid speculation about ambiguous stimuli. But rigidity is not an either-or characteristic; the extent to which a child is inflexible depends upon the interaction between his personality and the particular circumstances. If there is a generalized tendency to rigid behavior, it is much less likely to function in relatively simple, low-anxiety tasks which are performed without high-pressure testing.

Some psychologists argue that males are less rigid than females, because they are less dependent and submissive. Children of high intelligence are said to be somewhat less rigid than other children; they abstract and generalize more quickly, and they think more comprehensively, because they begin with more information and integrate into their cognitive structure a greater variety of facts and perceptions. Relationships between rigidity and age are even less clear-cut. Older children appear to be more rigid than younger children, but the apparent rigidity of older children may be the result of school instruction which emphasizes formal responses and narrow direction.

Divergent thinking, the search for new and different ways to do things, is much more likely to flourish in permissive classrooms. Teachers who, on encountering rigid behavior, point out its limitations in a friendly, encouraging way help children to want to try something different the next time. Children should be guided to look for more than one interpretation, for more than one way of judging, and for more than one way of acting.[96] Of course, the teacher should not push the children. Too much haste, despite the best of intentions, actually increases inflexible behavior, because time and effort are necessary to find and explore alternatives.

Concept formation

The formulation of accurate verbal and mental images is prerequisite to a rational understanding of the world. By the time children enter nursery school, they have acquired a considerable number of more or less accurate concepts by which they interpret everyday experience. For the purposes of this book, a concept is defined as a unique quality common to a number of objects, processes, phenomena, or events, which are grouped according to this unique quality. Therefore, in order to form concepts, children must be able to abstract these unique qualities from the raw materials of experience. The young child may regard a rock as in adult terms, a large, solid, gray, heavy, naturally occurring substance. As children grow older, their conception of a rock becomes progressively more precisely defined—"a natural material which is a component of the earth's crust"; at an even higher level, they see it as an aggregation of one or more different kinds of minerals which may occur in varying proportions.

The literature of education provides many examples of the greater efficiency and retention of learning through generalization and conceptualization, which contrasts sharply with the short-term learning of individual facts. "*The effect of concept learning is to free the individual from control by specific stimuli.*"[97] He is no longer forced to recall the individual events from which this learning came. The test of conceptual mastery at any level is the ability of the learner to identify a new event with a particular concept, and thus to endow it with general properties. The conception of energy, the ability to do work, in its electrical, chemical, mechanical, and thermal forms, is a liberating idea because of its potential for increasing understanding of the physical universe.

It is obviously impossible to present to the learner all of the individual events in which energy is involved. But if the learner has created an "image" of energy from experience, he is better prepared to recognize its presence and pertinence in other occurrences. "Energy" now summons a whole host of related meanings, which the child can use fruitfully because others understand it in the same way.

The capacity to repeat a definition of energy does not imply that a child has mastered any of these meanings. This kind of verbalism is a sign that his concrete-empirical experiences are either inappropriate or inadequate. However, once the conception is formed, it may be coupled with additional conceptions to form a principle (e.g., the potential energy of a falling body is converted into kinetic energy).

The assertion that direct experience is necessary for the formation of scientific concepts and principles has been verified many times, and it is well accepted by educational psychologists. It is most unlikely, however, that important scientific concepts will be discovered and identified by unguided children. Butts demonstrated that unguided children of superior intelligence, socioeconomic status, and scientific awareness fail to pick out the important concepts and generalizations from simple scientific experiments. In one of his studies, Butts devised four physical experiences which were designed to provide sufficient empirical knowledge to formulate the concepts of displacement (two objects cannot occupy the same place at the same time), inertia, action-reaction, and depth-pressure relationships. Children made some progress toward forming these concepts, but few achieved more than a rudimentary understanding.[98]

Let us suppose, however, that a skilled teacher had planned these experiences in cooperation with the class and that the experiments had been discussed as they were being performed by the children and at the end of the experimentation. We would reasonably expect more efficient and meaningful learning from this kind of guidance than from children who are left to discover for themselves. The Piagetian notion that manipulation of concrete materials paves the way for concept formation is pertinent. The skills, so to speak, are stored, and can be combined at the appropriate time. Hunt points out that the roots of space, time, and causality, to cite but three conceptions, lie in the infant's testing of motor skills as he throws, climbs, walks, and plays.[99]

No single formulation of a scientific concept is complete; concepts exist in hierarchies of meanings which range from the very simple to those which are expressed in abstract and theoretical symbols. Teachers should look and work for a gradual growth of sophistication as individual concepts are elaborated and transformed by new learning. It is helpful to point out to children whenever possible that there are other meanings to the terms which they use. From the conception of an animal as a living, growing, reproducing creature dependent on food, air, and water to the classification of animals as vertebrates and invertebrates, there is a rapid increase in the depth of meaning of the "animal" concept.

Once established, an abstraction is more or less stable. It can be used without any further need to refer to its concrete-empirical foundation. Learning which is conceptually oriented is much less likely to be forgotten than learning of isolated facts or principles.

As children grow older, they become less and less dependent on direct experience for the formation of concepts and principles. Their own knowledge has increased or is potentially able to increase so enormously that verbal learning is more and more effective. It is doubtful, however, that many scientific concepts will ever have meaning without either direct or indirect ties to concrete experience. The conception of the atom, for example, may be formulated intuitively. But if it is formulated by intuition alone, it will bear little resemblance to the atom of modern physical science, which, although far removed from direct experience, is still dependent on that reality.

Teachers must always be alert to distinguish between verbalisms and the ability to apply concepts to clarify physical events. Children who use the terms "atom" or "energy" may visualize something which has little or no relevance to the atom of scientists, something which is a fantasy. Almy writes of the bright kindergarten child who explained why objects adhere to a flannel board. His logic seemed to be impeccable when he said that the covering of the flannel board was rough, and that the material on the back of the object which adhered to it was also rough. However, to the question of whether or not a piece of paper would also adhere to the flannel board, he replied transductively that it would not, because it was "round," where the objects which stuck were not round.[100]

The structure of the English language contributes to the confusion which engulfs children. What are children to think of expressions such as "live coals," "live wires," and "dead cells," phrases in which "live" and "dead" are purely figurative?[101]

Concepts of conservation

Piaget believes that a necessary precondition for formal, logical thought is a broad concept of "conservation." Conservation is defined as the awareness that many physical changes are reversible and that nothing is lost by these changes. By the age of seven to eight, according to Piaget, children accept the necessity for conservation of quantity, and therefore are confident that the amount of material in an object will remain constant, no matter how it is distorted. Seven- to eight-year-old children are ready for conservation of quantity because they have already mastered the complementary operations of reversibility and compensation. Compensation means that what is taken off here neutralizes what is added there. Children of this age are able to perform these operations mentally.

Lovell reports that in one experiment which he conducted in an English elementary school about one-third of the seven- to eight-year-olds were "conservers," and another third were in a transitional stage (i.e., when conditions were somewhat different, they became non-conservers). This experiment was a replication of Piaget's experiment using changes in a plasticine "sausage" shape. Two-thirds of the eight- to nine-year-old children, three-quarters of the nine- to ten-year-olds and nearly all of the ten- to eleven-year-olds were conservers. Yet when the conservation of an alternately stretched and unstretched rubber band was presented, a third of the plasticine non-conservers were conservers, and some of the plasticine non-conservers conserved the quantity of a liquid which was poured from one container into another of different shape. Obviously, the kind of stimulus is an important variable. Lovell suspected that the previous experiences of children were likely to exert a significant effect on their judgments of conservation.[102] Children must compare a simultaneous change in *two* aspects of matter, and make *two* judgments, in order to compensate for the distortion which they observe. They must also either accept or invent the notion that matter is formed of particles which change position when an object is distorted. This is an "atomic" concept to which the concept of reversibility must be joined.[103]

In another of the many experiments under Piaget's direction or inspiration, equal-size lumps of sugar were dropped into identical glasses filled with the same quantity of water. The rise in the water level and the increase in weight of the solution were pointed out. The response of young children, that the sugar simply disappeared, is a non-conservation concept. They expected that the level and weight of the water would somehow return to the original state and its sweet taste would remain, unaccompanied by other physical attributes. Older children, however, were aware that the increase in level and weight was a necessary and "permanent" consequence. Their thought pattern appeared to depend on these ideas:[104]

1. Small pieces of sugar are formed, but there are more pieces (compensation).
2. These pieces could be seen if their eyesight were sufficiently sharp.
3. These pieces can be reconstituted into their original shapes.

Weight conservation, which is distinctly different from quantity conservation, is a later development, perhaps because weight is not visible. It is not until the age of nine to ten that a large number of children can conserve weight. This is clearly shown by Lovell's repetition of Piaget's classic experiments with two plasticine balls of different densities. The smaller ball, filled with lead, was obviously heavier. After the experimenter rolled the lighter ball into another shape, children were asked to compare the weights of the two objects. Only 4 percent of the seven- to eight-year-olds were weight conservers; that is, they did not believe that the rolled-out ball was heavier because of its change in shape. This percentage increased to 74 in the ten- to eleven-year-old group. Many children who did not conserve weight were still able to think reversibly, because they remembered that the two balls were not equal in weight in the beginning. Lovell suggests that reversibility of thought, although necessary for conservation, is not sufficient for its mastery.[105]

Conservers of plasticine weight were not as successful in predicting conservation when water changed to ice, or in anticipating constant weight as a ball of clay hardened. Most of the conservers, however, predicted the weight constancy of butter which was permitted to harden. This is additional evidence that the nature of the situation, with its different perceptual and environmental stimuli, is an important variable in the thought processes of children.

It is justifiable to say that younger children do not conceive of weight as an attribute of the quantity of matter; that is, they do not visualize weight as a measurable property which changes only as the quantity of matter changes. (The physics of this statement is somewhat inaccurate.) Some children believed that squeezing somehow changed weight. The kinds of experience children have had seem to be very important. Their success with butter is perhaps the result of many experiences with butter, such as buying it by weight. Few children who play with plasticine notice its weight. As Lovell puts it, "Until the child has learnt from experience that warming, cooling, squeezing, hardening, ageing, lengthening and so on do not alter the weight, he will not conserve weight in the widest sense."[106]

The influence of perceptual stimuli in judging weight is significant. The child thinks of weight as a downward push. The push produced by a weight is greater than that of the same weight when it is flattened out.[107] The direct sensation of concentrated push is disregarded only after many different weight-volume experiences which are reinforced by the evidence of physical weighings.

Conservation of volume develops still later. Children younger than six do not recognize conservation of volume. Even at the age of ten to eleven, many children fail to predict that equal volumes of water are displaced by equal volumes of different shapes. They fail to foresee what will happen when small and large displacers are lowered into water-filled jars.

Many children expect a heavy object to displace more water than a light object of the same volume. They are confused by the location of the displacer; they may believe that a displacer at the middle of a container displaces less water than at the top or bottom. The kind of container often enters into their predictions. These are irrelevant variables, but none the less, children must learn to sort them out and to discount them.[108] The difficulties of holding all variables but one constant are clearly to be seen in volume-conservation learning.

The physical technique of displacing water is confusing to children. In the usual displacement experiment, children are required to compare the physical volume of the object to the volume of water displaced. The logical necessity for these two volumes to be equal is not apparent. Children's first "atomic" ideas may compound these difficulties if their "atoms" change size according to position and the number of atoms which push on them. If children act according to this atomic model, they cannot give "correct" explanations.[109]

A number of investigators have discussed the desirability of accelerating mastery of conservation. If it were possible, such important ideas as buoyancy and density could be taught before children are eleven or twelve, the ages at which they evolve naturally. However, the children have not achieved stable learning when the attempt has been made. For example, Jan Smedslund sought to teach weight conservation to a group of children who did not conserve weight by working with light and heavy objects. The objects were of equal volume, but their weights were so different that size did not determine weight. In this way, Smedslund tried to eliminate weight as a necessary consequence of quantity. He was unable, however, to increase significantly the rate at which children became weight conservers. His result does not mean that acceleration is impossible, but rather that acceleration of this kind of learning may take much more time and planned experience than he gave to it.[110]

In another experiment with five- to seven-year-olds, Smedslund was somewhat successful with weight conservation by weighing objects on a balance and demonstrating that even when the objects were deformed their weight was unchanged. Some of the children transferred this conservation to situations in which objects were not first weighed. At first sight, these results appear to support acceleration of conservation.

However, it should be possible to extinguish a belief in conservation once it has been acquired if its maintenance is dependent on external reinforcement. But Piaget asserts that a genuine belief in conservation arises from maturational "necessity," and should therefore resist being extinguished. Smedslund tested these two hypotheses by a simple experiment. Using a variety of plasticine shapes, he first presented two similar forms of equal weight to the children. He then changed one of these shapes and secretly removed a piece from it. The children were asked to compare the two weights before they were weighed to reveal the inequality. The children were also invited to explain away the difference in weight.

None of the children who had "learned" conservation in the earlier experiment said that there was something wrong with the experiment. Half of the children who were natural conservers held fast to conservation of weight. Those who shifted seemed to accept weight change as a fact, explaining it by referring to different shapes: "rounder and fatter," or "bigger." The others asserted that clay must have been taken away or lost. Smedslund concluded that "conservation-learners" had really learned nothing more than "a relatively empirical law."[111] The pre-experimental explanations were similar, and it was impossible to predict responses from such preliminary explanations as this: "They [the objects] will weigh the same because they weighed the same in the beginning."[112] These words obviously did not mean the same thing to each child; therefore, it follows that words alone are insufficient to assess understanding of conservation.

Concepts of matter

The conception of matter which the first grader holds is specific and "use-oriented." A certain kind of stick is not a piece of wood—it is a popsicle stick. Children see only vaguely the relationships between objects of similar shape, hardness, color, or those made of the same materials but used differently (e.g., a wooden stick and a wooden ball). Scientists, on the other hand, are more interested in general characteristics for creating systems of classification than in specific uses. First-grade children, however, can learn to describe and to classify objects according to physical characteristics. For example, at the Berkeley campus of the University of California, first graders who follow a planned pattern of experience with objects and groups of objects characterize them as hard, smooth, or shiny. They divide groups of parquetry blocks according to such salient features as difference in shape or color. With this training, children are ready to classify natural objects which differ more subtly. These manipulative experiences with class inclusion strengthen their skill in describing physical objects according to their properties. They learn to distinguish quantitative likenesses and differences, a necessary skill in science. Lengths, for example, are compared to such arbitrary standards of length as popsicle sticks. The experimental objects are arranged into different serial orders, and new objects are added to these "ordered" groups. Still other activities are intended to improve understanding of conservation of weight and volume. For example, a ball of clay is squeezed and flattened; crackers are broken into bits; a ball and cylinder are formed out of different pieces of a lump of clay. Weight conservation is introduced as shapes change, as clay is subtracted, and as these forms are weighed on a simple balance with "standard" weights.[113]

Kinetic-molecular concepts

In one interesting experiment, Ulrich found that some elementary school children can profit from a short lesson on kinetic-molecular theory. Several demonstrations of kinetic-molecular pheonomena were presented to the children in order to help them form a "mental model" and become familiar with some of the variables. A day after the demonstration, Ulrich gave a ten-item multiple-choice test and an essay question on why water evaporates to 414 children in grades three to six. More than 40 percent of the third graders, 65 percent of the fifth graders, and 86 percent of the sixth graders achieved a mark of "70 percent" or more. The experimenter concluded that many children had either known or quickly learned some of the ideas of kinetic-molecular theory, despite the fact that the lesson was given entirely as a lecture demonstration without discussion of any kind. These children successfully identified in a drawing the "positions" of molecules in a solid, they labeled heat as increased molecular motion, they explained expansion caused by heat as a result of molecular motion, and they agreed that the three states of water contain the same kinds of molecules.[114]

This experiment is open to the criticism that the children simply verbalized without real comprehension. After all, by no stretch of the imagination could the demonstrations *prove* that water molecules are unaffected as water changes to a gas. Therefore, it is possible that the children merely repeated what they were told. There is no evidence that they were conservers of molecular number—that is, that they knew the number of molecules in a given volume must remain constant, even when conditions of pressure and temperature change. This conception is a necessary part of *kinetic-molecular theory.*

In a study by McNeil and Keislar, primary-level children were taught an abstract scientific language by a programmed teaching machine. The evaporation and condensation of water were said to occur because water is composed of moving molecules which attract each other. The effectiveness of this attraction was said to depend on the velocity of the molecules. Children studied drawings in which molecules were represented by dots or circles, velocities by vector lines. A series of "molecular" drawings was interpreted by children as representing liquid, solid, or gaseous states, depending upon the "velocity" of the "molecules" and their "distance" apart. Each child sat through twenty-minute individually programmed lessons which were extended over a period of several weeks.

Following a series of individual interviews with the children at the end of the formal instruction period, the experimenters concluded that the behavior of most children had changed as follows:[115]

> [They gave] correct verbal responses to oral questions about molecular movement, which the controls could not. When facing problems during the instructional period, subjects were able to predict that a gas would tend to expand throughout the whole space available and to indicate that gases can be changed to liquids by reducing the speed of the molecules. In the

> formulation of the abstract concept of molecules, pupils discovered (a) identifying detail and (b) relations by which they classified a series of instances. For example, subjects were able to read and interpret symbolic diagrams by which they classified physical phenomena depicted before them. The finding is important in view of the belief that diagrammatic materials cannot be used to express science concepts to young children... Differences with respect to the use of words by control and experimental subjects were also noted during post-test questioning, e.g.:
>
> Question: "How does a balloon get big when you blow air into it?"
> Answer: (control) "Cause it gets more air into it."
> Answer: (experimental) "Cause lots of molecules are going into it."
> Question: "How does the dew get on the grass?"
> Answer: (control) "Smoggy in the night—little bits of rain come on the railing sometimes."
> Answer: (experimental) "Water vapor in the sky falls down."

This experiment has been vigorously criticized as nothing more than a device for giving children a different vocabulary for animistic or magical explanations, and because concepts such as molecules were not related to "everyday objects" in the first grader's life. The first item in the program was "Can you see water vapor in the air?" The child who answered "No" was told "Right! Of course not... molecules are too small to see." The critic wondered if children had asked this question: "If molecules are so small that we cannot see them, how do we know that they exist?"[116] He remarked that "it would seem reasonable to suppose that 'molecule' and 'fairies that trade dimes for baby teeth' mean about the same thing" to a six-year-old child.[117] He also questioned some of the "correct" responses. For example, "molecular attraction" as an answer to the question "Why did a cold glass get wet?" is "not more scientific an answer than 'it perspires'."[118]

The use of scientific terminology is not the same as giving a scientific explanation. The productive scientist does not fix a pattern of answers to a set of questions. On the contrary, he is productive *because* of the *questions* he asks:[119]

> It is important for the child to learn that science and scientific theory do not have all the answers. Perhaps behavior which approximates an experimental environment where the *child* must ask many questions and *do* many things to get *some* answers would be more appropriate.

It is probably not until the third grade that kinetic-molecular ideas begin to become meaningful to children. Dennis, in a modest but well designed study, showed that a model of the kinetic-molecular theory could not be formed by children whose mental capacity was less than that of normal third graders.[120]

Concepts of probability

If it were possible to rate all scientific concepts according to their importance, the concept of probability would undoubtedly be one of the first. By probability, the scientist means that "all knowledge of what we call the physical world is... spread out over a spectrum of probabilities with one end so highly probable that in our usual frame of mind we consider it as 'quite certain'."[121] The idea that the only certainty is the certainty of chance is not easily grasped by children. Even in so transparently simple an event as measuring the length of a table with a ruler, the results, under the best of conditions, are only estimates of the most probable length—for example, three feet, six and one-eighth inches plus or minus a sixteenth of an inch. Acceptance of the consequences of chance in scientific experience comes with fundamental changes in the child's outlook, both philosophical and practical. Piaget hypothesizes that the notion of chance emerges during the concrete-operation stage of child development (ages seven to ten), when the necessity for things to happen is differentiated from the probability that they will happen. In the presence of multiple possibilities, the child begins to distinguish between certainty, probability, and possibility. The higher thought processes, in which abstract and symbolically phrased predictions take probabilities into account, come into existence during adolescence. It is only then that the child systematically visualizes the combinations into which individual elements of his environment may be arranged, and their relative probabilities of involvement.[122]

In order to identify events as "chance," the child must first know events which are not chance. That is, there must be some way for him to contrast lawlessness with law, chaos with order. As Flavell puts it, "a mind which knows no law can know no lawlessness;" during the preoperational stage of development, the child cannot differentiate between chance and non-chance, between order and disorder, between what is possible and what is necessary.[123] To him, nothing is logically certain, nor is anything genuinely chance. As he enters concrete operations, he discovers that despite his best efforts he can only guess about the outcome of many events. He also learns that he can make *reasonable* guesses about the outcomes of many events, and that some of these outcomes are more likely to occur than others. The concrete-operational youngster recognizes chance occurrences, but, without the mental equipment of the adolescent, he is unable to cope with them in a consistent, rational way.

This general outline of cognitive development leading to probabilistic thought has been fairly well accepted. Some investigators, however, argue that Piaget's tests depend on verbal skill, and therefore the existence of probabilistic thought in young children who recognize the effect of chance but are unable to express this awareness is disregarded. They point to the fact that very young children know and anticipate that other children do not always behave in the same way, or that their favorite toys do not always work properly.

To test the hypothesis that young children have an intuitive understanding of probability, Davies conducted an experiment with children from three to nine years of age. She confronted these children with a mechanical device which would supply the subject with a marble of a particular color if the child could predict the sequence of marbles by some kind of probability analysis. Older children were more successful with this non-verbal test, yet even at the age of three, 50 percent of the children selected the correct levers to press. Most five-year-olds responded correctly, although only a third were able to give oral predictions and to explain these predictions. By the age of seven, virtually all of the children expressed their explanations as probabilities. The experimenter concluded that non-verbal understanding of event probabilities arises before verbal statements.[124]

The effect of incorporating probability-centered science experiences in the nursery and primary grades is not yet certain. It is reasonable to expect that this kind of enrichment will facilitate formal probabilistic thinking when the appropriate cognitive tools are at hand. Avoiding probability and chance experiences in the primary grades appears to be unwarranted, because children seem to be able to assess event probabilities intuitively. The commission which designed the American Association for the Advancement of Science curriculum has recognized this capacity by including a number of experiences directed at extending the child's capacity for probabilistic thought.

Some selected concepts

Many studies of children's scientific concepts assume that young children are too unsophisticated to separate possible happenings from those which are impossible or imaginary. They also assume that the children's concepts are so naive that effective science teaching cannot make use of them. Such investigators as Haupt, King, and Yuckenberg, however, have demonstrated that this is not necessarily the case. Haupt questioned many children in an effort to learn what their concepts of the moon were. Some first graders, asked about the size of the moon, gave such answers as "as big as the town," "two inches around," "half a mile or a mile," and "big as the sun." A number said that the moon was "bigger than the world." Many made quite reasonable comparisons. Although most were unable to describe the moon's composition, several said "mountains," and a number described it as "a great big boulder," "sand and rocks," "rock," etc.[125]

King asked more than a thousand children the question "What is the sky?" Not more than 10 percent gave answers which he categorized as fantasy. Six percent of the children gave "false explanations"; 13 percent said they didn't know. The remainder gave either "true explanations" (12 percent), "true descriptions" (32 percent), or "false descriptions" (27 percent). The percentage of explanatory answers increased with age, as the percentage of descriptive answers decreased.[126]

Yuckenberg studied the preinstructional ideas of first graders about the sun and its effects on earth, and the causes of night and day, the moon, and gravity. She concluded that they were unable to visualize the immensity of the sun, which is a difficult task even for adults. Children compared the size of the sun to houses, to airplanes, to "ninety-one round pans you cook in." Although their conceptions of the sun's distance were also vague, they knew that it is far away. They knew that it is hot, but did not know, of course, that it is a star composed of incandescent gas. They were aware of some of its effects on the earth, and were intuitively aware of its relationship to day and night. The following is typical of their answers:[127]

> Investigator: I wonder why we have night and day. Where was the sun when it was dark last night?
>
> Answers: a. The sun turned off and the moon turned on.
> b. It's just sort of magic, the sun and moon move.
> c. The moon made the sun go into the clouds.
> d. The sun goes over to where the cowboys live when it is dark.
> e. When it is dark the sun is right on the other side of the world.
>
> Investigator: Some one talked about gravity. What is gravity?
>
> Answers: a. Gravity is plain dirt, only it is like a magnet.
> b. It is some kind of air that keeps everything on earth.
> c. It keeps us from going up into space.
> d. It's stuff that keeps you on the ground.
> e. If we didn't have gravity we'd never come back to earth.

Many of these answers show thought and pertinent knowledge. The children often responded with genuine, albeit intuitive, explanations. In terms of their framework of knowledge and understanding, their answers made sense. Surely, such children should not be denied the opportunity to learn much more about astronomy if they are ready for it.

Concepts in mathematical botany

The new insights which creative scientists bring to the emerging elementary curricula are well illustrated by this account of botany instruction in the second grade:[128]

> I must begin by teaching them the ordinary parts of a plant; the stems, the roots, leaves, and buds. After they have learned these, I call their attention to the fact that every leaf has a bud in the axil. This is called an "ordered" pair.
>
> If you will look at a tree with ten or twenty thousand leaves on it you will find that every normal leaf has a bud in its axil. The leaf lies between the root and the bud, and the bud lies between the leaf and the tip. I asked the children to map that relation on a stick. All of them could do it. Thus they can map a concept on a stick. Then I call to their attention that the root precedes the leaf, precedes the bud, precedes the tip as you go up the stick to indicate an ordered formula. They had just been introduced to equations two weeks before. One little youngster said, "This is just like an equation." Of course, there are some differences, naturally, but none the less, it is a mathematical statement that they have become aware of.
>
> Then we give them a notation to represent these things, *r* precedes *b*, precedes *t*. Next, we say "We want to use this little model, this little map you have made, to discover hidden knowledge." In the first exercise, we give them an ordinary willow stem about four inches long. We selected the stems so that they are just about as thick at one end as the other. We told them, "Place the sticks on your desk according to your model so that the base is on the desk and the tip is in the air." Two of them missed it; all of the rest were able to do it. Of the two that missed, one was just careless. She knew the answer, but the other one was confused. All of the rest of them got it and knew why they were right.
>
> The next thing we gave them was an ordinary white potato and said, apply your formula now to the white potato and see what the potato tells you. The teacher was told she was not to ask them any questions except, "What else does the potato tell you?" The first question was, "Do you see anything that looks familiar?" One little girl said, "I think I see something that looks like a bud." A little boy said, "Oh, that's just an eye." He did us a very great service because he gave us a vocabulary to work with. Then a youngster frantically waved his hand and said, "If the eye of a potato is a bud, according to my model the eyebrow is a leaf scar." He was using his mathematical model to arrive at something that never occurred to him before. The next youngster said, "If the eye of the potato is a bud, and the eyebrow is a leaf scar, the potato must have a base and a tip." He made this deduction by being prodded only to see what else he could discover.
>
> The teacher then said, "Place the potato before you on your desk so that the base is at your right hand, the tip on the left." There were 39 youngsters and 39 got it right. They could use this model in the second grade and reach effective answers.

Here is concept learning which links the worlds of mathematics and living things in a new and exciting way. The value of a theoretical model, rooted in rich experience, for predicting and verifying new observations and new relations is vividly illustrated. Of course, the twigs and potatoes are concrete, in sharp contrast with the molecules and atoms with which other concept-teaching experiments have been concerned. This model which organizes such concepts as leaf, axil, bud, root, and tip in a serial order led to the discovery of new knowledge by children so young that their success was completely unexpected. Direct experience with concrete materials seems to be absolutely necessary in order to form the model, but once formed, it is generalizable to new situations. The lesson described above is a fine example of guided Inquiry.

Some problems with concept formation

Despite the many dozens of research studies of concept attainment which have been published, our awareness of those concepts which are both meaningful to children and scientifically accurate is still somewhat fragmentary. The majority of these studies have been so narrowly focused that their conclusions are not of great help in the classroom. The data, however, support strongly our belief that the ability of children to understand scientific concepts has been underestimated in the past. For teachers, the important questions are these: What levels of conceptual sophistication can we expect of children in the various grades? How much more abstract and generalized is a sixth-grade concept than a third-grade concept? What kinds of experiences lead most efficiently to understanding? For each conceptual sequence, is there a corresponding experience sequence which is best? How must these sequences be organized to meet the needs of children who are different in their preparation, intellectual ability, and motivation for learning?

Even if second-grade children are potentially able to grasp the meaning of density—and this is doubtful—is density so important a concept in science that "excessive" time be devoted to it? Or, on the other hand, should simpler concepts come first, even though they are less important? The answers to these practical questions are not known, but there is good reason to believe that they will emerge from the intensive research in child development and learning which is now in process.

Transfer of learning

Two kinds of transfer of learning have been proposed:[129] *applicational transfer*, which is the application of facts and principles to a new, but related problem, and *aptitude gains*, which is a generalized way of looking at and dealing with ideas and phenomena in special contexts. Both kinds of transfer can be achieved in science learning, and both are important objectives of science education, although aptitude gains are more likely to be of enduring educational value. Each has a part to play in the child's continuing encounter with the structure of knowledge. When Bruner says that "to learn structure . . . is to learn how things are related," he refers to facts, concepts, and principles, and to the extraordinary importance of their relationships. When the meaning of the conceptual scheme "We live in an ocean of air" is truly understood, it is because concepts of pressure, buoyancy, force, density, volume, gas, liquid, and fluid have been inter-related. This richness of meaning leads naturally to explanations of why balloons are able to float in air, and to comparisons with a ball floating in water. It confirms the scientific belief that man can "explain" his natural world with the procedures and conceptual framework of the sciences.

The new elementary-science curricula pay a great deal of attention to the ways in which scientists approach these problems, because these curricula are committed to the need for transferring Inquiry skills. Suchman has verified this transferability, not as codified rules, but rather as attitudes—for example, confidence in dealing with raw data, in proposing hypotheses, and in trying new ideas.[130] There is, in addition, a considerable body of evidence that children who are trained to think analytically are more successful with new problems.[131] Even though an adolescent who is at a generally abstract level of thought must begin at a concrete level in a study which is new to him, he moves quickly to a higher order of abstraction because of his intellectual style and competence. His stronger vocabulary and capacity to think symbolically, the larger body of facts and concepts at his disposal, and his previous experience in discovering relationships are the factors which enhance this generalized transfer.[132] The success of mathematically able students in physics courses is one argument for the validity of this proposition.

The problems which confront classroom teachers, however, are not appreciably eased by experimental proof that transfer to new but related situations is possible. The phrase "new but related" is difficult to define in operational terms. How new? How related? May it be that there are no psychological associations in some phenomena which seem to be both visibly and logically related? An experiment by Ervin in applicational transfer provides some insight into learning when the psychological demands of the problem change. In this experiment, which is modeled after one of Piaget's, children play with a toy truck running on an inclined plane. The truck, drawn by weights, is affected by three variables; the weight of the truck, the weights which pull the truck, and the slope of the inclined plane. The children were trained to predict the direction in which the truck would move when two variables were changed. They were then tested for the amount of transfer when all three variables were altered at the same time. The children were third and fourth graders, with a median IQ of 120. Most of them completed the assigned training tasks successfully. Only half, however, succeeded with the three-variable problem. Children with higher IQs and those more competent spatially and verbally were significantly better at the latter task. The investigator suggests the possibility that the two tasks, two-variable and three-variable, were not really identical or even closely similar. The variations, some of which were supplementary—that is, they all operated in the same direction—or else complementary, with one variable opposing the other two, were much more complex than in the training tasks. It was much more difficult for children who lacked direct experience in manipulating all *three* variables at once to pick out the opposing effects and to predict their interaction.[133]

It is probable that there was too little time for many of these children to grasp the nature of their task and to achieve a high enough level of familiarity with the variables. As Ausubel says, "Prior learnings are not transferable to new learning tasks unless they are first overlearned," and overlearning was obviously not incorporated in the experimental design.[134]

There is an unfortunate tendency for some teachers to present a fact or idea once, and then to assume that it has somehow been transformed into active knowledge. Experienced elementary school teachers are much too wise in the ways of children to count on immediate retention. They know that repetition, review, and diversified learning tasks, coupled with evaluative feedback, are important teaching tools. They know, also, that the fine line between motivational repetition and boredom is often indistinguishable even to the master teacher.

All children do not generalize to other contexts and use multiple solutions to problems equally well. No one is quite certain of the extent to which these inequities between children come from differences in knowledge and experience, or from hereditary factors, or from both interacting in some complicated maturational and developmental way. The broader the concepts which have been learned and the more varied the experiences in which they are encountered, the greater the probability of successful application. When the pertinent abstractions are genuinely the child's and the new problems are not beyond a conceptual match, the probability of transfer is increased, although never made certain. Previously assimilated learning is surely of great importance. Transfer cannot occur unless something has first been learned. But, as a corollary, the teacher must provide many opportunities for applying this learning. In the sciences, this is a call for teachers to provide the richness of experience which has been previously recommended—not merely to provide experience for itself, but rather to give children the chance to cope with it, analyze it, interpret it and capitalize on it as completely as possible.

Acceleration of learning

Educators and interested laymen have often advocated accelerating the learning of young children, an idea which is opposed by those who interpret Piaget's developmental stages in a narrow, restrictive way. For example, some writers may say that since density is a meaningless concept to young children, there is no point in including experiences with density in primary-grade science. Piaget, however, is not a teacher. He made no attempt to teach the thousands of children who were his experimental subjects, and there is no real evidence to refute the notion that well-planned instruction in science will help children to pass much more quickly to the level of propositional thought. Children have effectively learned many ideas once shunned as too difficult for them. Many other ideas, however, seem to demand too high a level of experience, mental structure, and expertise for young children. It may not even be possible for youngsters to grasp them intuitively.[135] Or, on the other hand, "proper training" may be successful in achieving some presently unknown maturational limit. These ideas are conjectural as yet; research directed at accelerating Piaget's stages by well planned and *long*-term teaching is almost non-existent.

As long as a child is dominated by perceptual behavior, he will miss the abstract ideas embedded in scientific experience. A three-year-old can probably be taught to use words which seem to represent abstract ideas, but he will not know what they mean.[136] Preoperational children may be trained to assert the conservation of quantity, but, as Smedslund demonstrated, this concept is easily destroyed. For example, some young children who have been trained to recognize the effect of the length of a see-saw in balancing the see-saw accept the suggestion that the color of the weights at the ends of the see-saw affects its equilibrium. Older children reject color as irrelevant.[137]

Training in specific tasks is unlikely to produce significant learning, because it has little effect on the child's general pattern of thought, and therefore it is false learning. Indeed, tasks taught too early may waste time because they do not improve long-term learning. The teacher should be aware of the possibility that too early an exposure to a concept such as weight conservation may result in slower learning of other concepts, such as transitivity, and, therefore, the child may lose in general growth what he gains in specific growth.[138]

Forcing the child *too* rapidly to abstract symbolic thought may actually inhibit learning. Children who encounter a wide variety of concrete experiences and are encouraged to respond imaginatively and analytically will be better prepared for abstract thought. But more time, not less, is required.

Although most studies of accelerated problem solving behavior in children have been discouraging, the important work of Anderson is much more optimistic. Anderson sorted sixty bright first graders into control and experimental groups which were equated by sex, mental age, and chronological age. After a series of twenty-seven twenty-minute training sessions, these children were given a series of problems, some of which were similar to their training tasks, some of which were more difficult. The children were taught to change the experimental variables one at a time while holding the other variables constant, in order to "demonstrate that when presented with suitable training, children will acquire and transfer a rather advanced, complex problem-solving skill."[139]

Most of the children in the two groups achieved the criterion of mastery before moving on to the next training tasks. Ten children failed the most difficult training task, which was to select from eight leaves the leaf which exemplified a particular combination of three characteristics. Leaf characteristics chosen were pinnate or palmate, simple or compound, and smooth or notched margins.

Two of the test problems were derived from science. One was a pendulum problem in which the variables were pendulum length, weight of the bob, and the angle at which the bob was released. The task was to "figure out what makes this swing the most times in ten seconds."[140] The second problem, a variation of a Piaget experiment, was chemical. The children were required to find "which bottles you have to use to get yellow."[141] Only three of the five bottles of reagents which were on hand were necessary. The other problems were simpler in that they could be solved without combining or changing the materials and they did not depend on a series of mental combinations. They were of the multiple-concept discrimination type—for example, selecting unsharpened eraserless pencils from a group of twelve pencils of differing lengths, with or without erasers, sharpened or unsharpened. The experimenter pointed to each pencil in turn, saying "This pencil shows my secret" or "This pencil does not show my secret." The children were then expected to select pencils with the proper combination of characteristics and to explain the reason for their choice.

The experimental group was significantly superior to the control group, except in the pendulum and chemical problems; but even in these two, the experimental group was somewhat more successful.

There was no reason to expect significant transfer to these two problems, because they were on an entirely different psychological level. It is possible, however, that training directed at "conceiving combinatorial possibilities" will also help children with such problems as these.[142]

Since the skills which were successfully taught do not spontaneously occur in six- and seven-year-olds, it is reasonable to expect that, with practice, children "can acquire, retain, and transfer rather complex problem-solving behavior."[143] No sex differences were found, nor was the order of the tasks significant. There was no attempt to arrange tasks in any kind of learning and testing sequence.

Inquiry

Throughout this book, we have strongly emphasized the value of Inquiry procedures in science instruction. Unfortunately, there is no large body of experimental evidence which testifies to the effectiveness of Inquiry in leading children to a more coherent and deeper knowledge of science content, principles, and theories. The limited research in Inquiry only hints, rather than proves, that this kind of learning is facilitated. Certainly Inquiry is not an effective tool for teaching an extensive collection of facts and principles. The function of Inquiry is rather to rescue children from the deadly boredom of rote science instruction and demonstration and, by encouraging them to rely to a greater extent on their own resources, to help them attain more important goals. It may be, as McDonald suggests, that Inquiry research, as it has been carried on, is too limited in technique and approach, and, we may add, too cursory, to produce evidence of effective mastery of content. He adds, however, that if discovery is "carefully programmed" and guided, "it proves to be an effective method."[144]

The debate on Inquiry teaching is confusing. Bruner has postulated a number of strengths which he believes are inherent in this approach. (See Chapter 4, p. 140.) Psychologists have pointed out the additional involvement of children in problems which concern them, an interaction which increases attention and effort. For the child who is genuinely involved, the importance of the task is increased, and with it the need for intellectual endeavor. Success gives the child increased confidence in his ability to think, strength to be independent, and a minimizing of inner conflicts, because he is no longer passive. Of course, the often cited "joy of discovery," which thrills both the child and the teacher, is an important incentive.[145]

Discovery procedures, at least with elementary school children, are in harmony with the developmental theory of Piaget. The demand for direct experience with nature, and the requirement for children to act on and in turn to be acted on by these phenomena is, if not uniquely a Piagetian revelation, at least consonant with his psychology. It may be true, as Suchman remarks, that those children who are able to deal with raw data, who leap beyond data to develop a hypothesis, who generalize and hypothesize, and who are autonomous learners make the best inquirers.[146] This conclusion does not mean that science taught by Inquiry should be restricted to these children. If children begin with a concrete problem, if they know that, with the assistance of the teacher, they can find the necessary information and be guided to a solution, but that they will not be *given* the answers, they will make significant progress toward the pertinent goals of elementary-science instruction. In Suchman's words:[147]

> When you present children with problems in very concrete terms, without the esoteric terminology, the definitions, the symbols, and the other conventions of a formalized science, the children begin to go to work on these problems in logical and productive ways.

Hypotheses, correct and incorrect, will come from clear insights and adequate interpretations, but only if children are encouraged to meet the challenge of unconventional learning.

One of the sobering realities of education and educational research is that, as a rule, impressive gains do not result from educational experiments. There is little chance that a few weeks of Inquiry will produce gains of any magnitude, no matter how experienced or capable the teacher and her children. Bloom remarks that, at the University of Chicago, two or three years of intensive effort by teachers and researchers are required to find evidence of significant growth toward newly formulated objectives.[148] Objectives as complex and significant as mastery of the spirit and strategy of scientists are surely dependent on teaching insight and on prolonged experience with many kinds of scientific activities. We should always keep these wise words of Holt in mind:[149]

> We must recognize that children who are dealing with a problem on a very primitive, experimental, and inefficient level, are making discoveries that are just as good, just as exciting, just as worthy of interest and encouragement, as the more sophisticated discoveries made by more advanced students...the invention of the wheel was as big a step forward as the invention of the airplane—bigger, in fact... Above all, we will have to avoid the difficult temptation of showing slow students the wheel so that they may more quickly get to work on the airplanes. In mathematics certainly, and very probably in all subjects, knowledge which is not genuinely discovered by children will very likely prove useless and will be soon forgotten.

Arguments against inquiry

The recent revival of interest in Inquiry learning, and its possible overemphasis as a solution to the problem of poorly organized, memoriter, meaningless science instruction, has called forth a counterattack by many knowledgeable educators and psychologists. For example, Kagan argues that children of low intelligence or motivation cannot persist in tasks which are not immediately fruitful. He asserts that young children lack incentive to tackle problems because they have never experienced the fun and the ego-boost of success. Furthermore, because of intellectual and subject-matter limitations, they are unable to narrow problems sufficiently for success. Many children who are impulsive, who leap at answers, are likely to fail:[150]

> The method of discovery is most appropriate for highly motivated older children who might have high dependency conflict and who are inclined to use a reflective strategy...least appropriate for younger children, especially those below the age of nine, who do not have high motivation to master intellectual tasks and who tend to be impulsive.

Kagan also stresses knowledge of subject matter (a rich background) as a precondition for discovery learning.

Friedlander mentions the greater possibility of failure in Inquiry, a failure which dampens the interest of the young investigator. He points to the lack of evidence that retention with discovery is higher than retention with other teaching procedures. As has been noted, researches in content retention and transfer have been disappointing, yet most psychologists agree that there are positive transfer effects.[151] In Ausubel's words:[152]

> If learning by discovery promotes transfer in some unique way, it probably does so through the transferrable experiences of independently formulating and testing alternative hypotheses and through the transferrable attitude of independent search.

Ausubel, a vigorous critic of discovery methodology, insists that there has not yet been a conclusive demonstration that discovery transfers across the various disciplines.[153] However, if transfer within the framework of elementary science is facilitated, this is justification enough for teachers to employ Inquiry procedures more frequently and for longer time periods.

It is undoubtedly true that early success is a necessary condition, but appropriate selection of learning experiences by an experienced teacher increases the probability of success. It may also be that at first only a small number of children in each class will propose fruitful ideas and will make the inductive and deductive leaps which are required. This number will grow as time goes on. The conditions for this kind of thinking are not clearly defined at present; the role of conditioning and experience, although obviously important, is still vague. The teacher will continue to present some kinds of information directly, and will structure the investigation along lines which are inherently more likely to be successful. Discovery is certainly not the sole instructional method for elementary science. It is not imperative that children *always* find out for themselves. Yet, if problems are properly selected, direct instruction is less likely to be essential.

If it is a fact that only older children of superior intellect are capable of Inquiry learning, it will be foolish to delay the first contact with such instruction until the high school years. Years of learning by recitation in the elementary school are not easily transmuted by a single course in high school biology or chemistry. It is wishful thinking to expect the different patterns of thought and action required for discovery learning to occur in a few high school years without a long exposure to this learning in the elementary schools. Indeed, one of the most difficult tasks of the college science teacher is to convince students that it is possible and desirable for them to learn for themselves. The student's expectation of how he is to be taught and of what is expected of him is narrow and rigid. Few welcome the idea of self-direction, even under guidance.

The elementary school teacher should help children to organize their data, guide them to make the necessary jumps, and evaluate their results. The teacher must judge and help correct ambiguity, confusion, and misunderstanding. Friedlander states that "one of the goals of teaching and learning must be for students to accept the discipline of facts and skills as prerequisites for true understanding."[154] It is reasonable, however, to believe that children will accept a discipline that is otherwise meaningless to them when they themselves see the need for new facts, for new information, and for new experiments in order to find the answers to questions which interest them.

Summary

From the viewpoint of psychology, it is now clear that the learning capacity of children in science has been too long underestimated and that children have not been taught science in ways which stimulate cognitive growth. The new interest which psychologists are showing in classroom learning and teaching is a good omen for the years to come in that it will be possible to base teaching on a sound theoretical foundation.

Despite the fact that neither learning nor teaching theories are completely adequate, we know much that will help us to teach science more effectively.

Children differ cognitively in many ways—in creativity, insight, rigidity, and analytical and synthetic patterns of thought, to cite but a few of these differences. They are severely restricted in what they perceive, although training appears to improve perceptual ability. With experience and maturation, logical thought grows gradually from causal confusion into a mechanistic and formalized logic. This causal confusion, which is particularly noticeable as they manipulate variables, may be at least partly resolved by special training. This kind of acceleration is particularly desirable because experimental science is, in a real sense, utterly dependent on control of variables.

Children's "mental models" become more adequate especially as they are given attention, so that children are better prepared to give scientific explanations for which mental models are essential. With successful practice in problem solving, and as they cultivate a general approach to problems, children become more confident of their own intellectual strength.

There is general agreement that non-rigid, highly creative, intelligent children are ideal for Inquiry teaching. Creativity, however, is not a simple, intelligence-anchored capacity, but rather coexists in varying degrees with high or low intelligence. Children who differ in their creativity-intelligence ratios are surprisingly dissimilar in their cognitive, social, and emotional classroom behavior.

The desire to learn is one of the most important forces in education. Unless children want to learn, and actively work to restructure that which is presented to them, learning will be inefficient and superficial. Desire to learn is strongly affected by anticipation of failure or success, and by the degree to which the classroom provokes anxiety. Young children are attracted to scientific activity; they have a strong interest in science. The need for children to remove discrepancies in their experience is a powerful argument for science instruction.

The dependence of intellectual maturation on rich experience with the broadest range of phenomena and operations is now well accepted. For example, very young children profit from unhurried exercises in classifying objects and events into descriptive categories. As a result, several of the new elementary-science programs have incorporated many of these experiences for primary grade children into their curricula.

Children pass through a series of conceptual growth stages, from "direct," more or less unbranched thought to a complex, interrelated network of meanings. Most children at the age of five are non-conservers of quantity, weight, and volume, because they do not think reversibly, nor do they compensate for weight and quantity changes. They begin to conserve quantity at the age of seven or eight; they conserve weight at the age of nine or ten; and at the age of eleven or twelve, they conserve volume. Although short-term attempts to accelerate the acquisition of these concepts have failed, acceleration may be feasible given proper instruction and sufficient time.

The work of Piaget has contributed the most important analyses of the cognitive stages of child thought, although Piaget's developmental theory is somewhat complex and obscure. Piaget insists that children learn by reinventing and reorganizing experience, not by merely stuffing new increments of learning on top of old knowledge. This reorganization in the child is a creation of the processes of biological maturation, knowledge, and auto-regulation (assimilation-accommodation). Up to the age of two, the child lives through what Piaget calls the *sensorimotor period.* From two to eleven or twelve, he is in the period of *concrete operations,* which is divided into several sub-stages; *pre-conceptual,* from two to four; *intuitive,* from four to seven or eight; *mental concrete,* from eight to eleven. As the child moves through these stages, he shifts from egocentric and animistic thought to probabilistic thought, to mastery of such operations as serializing and classifying, to simultaneous consideration of two or more variables, and to mechanistic causality.

The values of Inquiry instruction have not yet been *proven* by educational research. Many studies yield ambiguous results. From the viewpoint of the learner, Inquiry is desirable because it encourages divergent thinking, freedom, creativity, and interest. Inquiry teaching, however, has been criticized on several grounds; for example, it has been alleged that only the most capable children are likely to be successful. However, the psychological potential of Inquiry instruction is sufficient to satisfy most elementary school children that *they* can learn for themselves, and *this* is the learning which will be permanent.

For further study

1. To what extent should the emotional and physiological differences between children condition the teaching-learning process?

2. Justify the following statement by Piaget: "Learning, in reality, depends on development, contrary to the widespread opinion that development is a consequence of a series of learning experiences."

3. What are the implications for science teaching of this statement by Piaget? "To comprehend is essentially to invent or to reinvent, and every time that one teaches too quickly an outcome of reflection, one hinders the child from discovering it or from inventing it by himself."

4. In what ways is perceptual growth dependent on physical activity?

5. What is the evidence for the statement that "logical thinking is the outcome of many experiences and physical activities"?

6. How adequate is the evidence that young children can formulate mental models which explain natural phenomena?

7. What is the relevance of Suchman's work on Inquiry to elementary school science?

8. In what ways may the teacher foster creativity in the classroom? How is creativity to be assessed?

9. Do the factors which affect desire to learn operate in the daily enterprise of teaching? Can they be adapted by classroom teachers so that they will help children to learn?

10. What are some of the reasons for the irrelevance of much research in educational psychology to classroom instruction?

11. Select a particular conceptual structure in the child and trace its development to the age of adolescence.

12. The authors assert that Inquiry is a meaningful approach to science learning. Have they sufficiently justified this statement from a psychological point of view? Is it possible to justify a claim of this kind?

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3

A hundred years of elementary school science

The place of science in the elementary schools has been vigorously defended almost from their beginning. An endless number of periodical articles and annual reports of school committees (boards of education) in urban and rural communities confirms the rise in popular interest in science during the first half of the nineteenth century. Such men as Henry Barnard and Horace Mann proclaimed the values of science in the schools to all who would listen. They believed that science teaching fulfilled three special functions: (1) theological, (2) utilitarian, and (3) disciplinary.

The theological goal

Science was held to be a direct confrontation with the handiwork of the Lord, uniquely fitted to develop in the child that deep understanding of God and God's purpose which must inevitably arise from the direct perception of the order and cosmological rationale of His world. The unmistakable evidence of purpose in the natural world which science revealed would engender the proper moral and ethical patterns of behavior. In order to discover God's design and purpose, it was obviously necessary for man to study his world, both the environment immediately at hand and the far-distant parts of the universe. This theological argument was perhaps more frequently proposed than any other in the continuous struggle to include the physical world in the narrow curriculum of the elementary schools. However, none of the proponents of science rested their case solely on the claim that science instruction was an essential adjunct to spiritual education.

The utilitarian goal

Educators often alluded to certain practical outcomes that, to them, appeared to be important. Surely, they said, the young boys who were destined to become farmers or mechanics would be superior farmers or mechanics once they had mastered the elementary principles of the pertinent sciences. This argument was often coupled with the statement that technological change was rapid and that traditional education was insufficient to meet the needs of the new society into which these boys would soon be thrust. This goal has survived in one form or another up to the present.

The disciplinary goal

The third reason for introducing science instruction was the belief that the materials of the sciences were peculiarly suitable for training the mental faculties of perception and comparison in children. Faculty psychology, the belief in the serial development of individual mental abilities, beginning with perception and comparison, guided educators during almost all of the nineteenth century. It was perfectly natural for Horace Mann to make this claim: [1]

> The objects of nature are pre-adapted to the development of the intellect... The objects of natural history—descriptions of beasts, birds, fishes... —should form the subjects of the earliest intellectual lessons. A knowledge of these facts lays the foundation for a knowledge of the principles of sciences, which respectively grow out of them.

It is significant that this "disciplinary" or "training" function of science has been reincarnated in some of the newest curricula in elementary science, although the naive assumption of individual powers or capacities has been abandoned, along with the belief that young children are unable to reason. The role of the sciences in nurturing a totality of intellectual skills is a noteworthy contribution of these new curricula. (See Chapter 6 for a detailed analysis of these curricula.)

Subsidiary goals of science instruction

Two other arguments advanced in the nineteenth and early twentieth centuries for teaching science are worthy of mention. Because science, often equated with nature, was held to be close to the hearts of children, it seemed that children would learn science quickly. This is a doctrine of innate interest, whose functional value is questionable. In addition, a "cultural" goal was frequently proposed. Because they assumed that the sciences were products of man's highest intellect, the proponents of science found it unthinkable that children could leave school without exposure to that thought. No man, they argued, could be an effective citizen without that understanding of the facts and principles of the world around him which was (or should be) one of the measures of the educated layman.

The reality

Despite these appeals for the study of science in the common schools, it was not often taught. How, indeed, could it have been otherwise? The majority of schools, particularly those in rural areas, remained in session for but a few months, during which time instruction in reading, writing, and arithmetic necessarily took precedence. Graded schools existed only in the cities. The one- or two-room schoolhouse, inadequately heated and destitute of even rudimentary equipment, was characteristic of the nation's schools. Scientific equipment, although readily available, was expensive and rarely purchased during these years, when such luxuries as blackboards, globes, and writing paper were scarcely commonplace. Many teachers had no more than a common school (elementary) education. In 1857, for example, fewer than 10 percent of the common school teachers in Massachusetts had attended a normal school; few were high school graduates. A mere handful had attended college, and this group was concentrated in Boston and in the other large cities of Massachusetts. If this was the professional education of teachers in the more populated centers, what could be expected of teachers in rural districts? Teachers who knew no science could teach no science. And, finally, teachers who did introduce science were unable to find appropriate texts or curriculum materials. Indeed, courses of study, with a few exceptions, date from W. T. Harris' outline of 1871 which is described on page 118.

There were, to be sure, occasional reports of lessons in natural history or natural philosophy (physics and astronomy). In a few schools and in a few towns, such series of science textbooks as Hooker's *Books of Nature* were adopted, but they were soon relegated to the closet. Science instruction for boys and girls of high school age *was* well accepted, and the common schools in towns which lacked a high school frequently presented some of the sciences in the guise of "the higher branches." On the whole, however, it is plain that before the Civil War the advocates of science had failed in their efforts to establish science in elementary school curricula.

Object lessons

The Civil War decade witnessed a rapid growth in the number and influence of public high schools, and the small number of common schools which once taught science abandoned it to the high schools. As the high schools took up the burden of the formal sciences, leading educators turned their attention to a new methodology, commonly called Object Lessons, as a "natural" mode of instruction in the lower grades. Object Lessons, vaguely derived from the precepts of the great Swiss educator Johann Heinrich Pestalozzi were the most widely publicized instructional method in the two decades following 1860.

The psychological foundation of Object Lessons was the belief in the serial development of the mental faculties. The early years of childhood were assigned to instruction in observing, perceiving, and memorizing. Children of grammar school age were believed to be capable of comparing and classifying. Not until they reached the age of thirteen or fourteen were they credited with the abilities to infer, deduce, and generalize. With these assumptions, the content selected for Object teaching is obvious. The primary grade teacher was expected to begin her teaching with a suitable object (a rock, an orange, or a cube), and to lead her children by skillful questioning to report the color, shape, taste, weight, texture, and other physical features of the object. Much of this teaching turned out to be a kind of vocabulary drill in which such technical terms as "amorphous," "argillaceous," and "excrescence" were typical.[2] With older children who had been "properly" trained in perception, the faculties of inference and generalization were to be developed by textbooks, charts, experiments, and, all too frequently, by verbalization. In Underhill's words, "Although Object Teaching started out as a means of emphasizing the part played by experience in giving meaning to words, it degenerated into the worst form of verbalistic memorization."[3]

Object Lessons were originally a method, not a course of study. They were drawn from all aspects of the environment in order to stimulate appropriate development of one or more of the faculties. Readily available materials, often of scientific interest, were selected for this purpose. For example, in the Oswego (New York) schools, which became internationally famous as a center of Object instruction, children from the ages of six to eight were carefully instructed in sorting and describing colored materials. Nine- and ten-year-olds learned some of the scientific reasons for color phenomena, and were taught to classify colors as primary or secondary. Henry Barnard witnessed one of the Oswego lessons on the chemical differences between acids and bases:[4]

> A class of boys and girls were arranged . . . so that they could observe the vials of liquids and solids upon the table in the center . . . The children were each given some cream of tartar to taste; they pronounced the taste *sour*. The name of the substance was written on the blackboard. Then they were given some sal soda to taste, and they said it tasted *bitter* and burning. The name of this was written on another part of the board. The teacher then told the children that we call those substances which taste sour *acids*, and wrote the word acids over cream of tartar. She then told them that the name for those substances which have a bitter, burning taste, is *alkalies*. This word was written over sal soda. Then the children were given some vinegar to taste.

Unfortunately, few schools were well equipped with the necessary materials, and charts were frequently substituted for real objects. Teachers, unaware of the theoretical foundation of their lessons, and untrained in the proper methodology, relied on "telling" in order to impart information.

There is no reason to believe that Object Lessons were ever widely adopted by the schools, despite the hundreds of laudatory articles which filled the educational press. The overwhelmingly accepted methodology continued to be memoriter recitation from textbooks, and relatively few instances of even this unsound science teaching are to be discovered. The history of education is frequently distorted by the appearance of fads which monopolize the literature. At first glance, Object Lessons appear to have been successful. But investigation of actual classroom teaching reveals that this was not the case at all. A method or a curriculum is merely a collection of words, and requires the active participation of teachers in order to breathe educational life into it. Elementary school teachers were never convinced that Object teaching was worthy of their participation.

Because some of the most recent proposals for elementary school science are surprisingly reminiscent of much that the leaders of the Object teaching movement advocated a century ago, the preceding analysis is instructive. These curriculum reforms, advocated by scientists and educators, are described in Chapter 6. It is undoubtedly true that history never repeats itself exactly, but a cautionary insight into the collapse of Object Lessons may provide guidance for evaluating current schemes for solving the problems of teaching elementary science.

One such problem has been described: The difficulty of providing a sufficient variety of objects caused teachers to be dependent on secondhand experience. In addition, Object teaching called for unusual knowledge of the properties and characteristics of objects and an intuitive awareness of how best to guide children in incorporating the desired percepts into their thought structure. When all books are forbidden, uncommon skill in "oral" teaching is indispensable. Teachers who were inexperienced in this adventurous business relied on amazingly detailed, "step-by-step" manuals to generate what critics sarcastically called "mechanic drill." "Oral lessons," really lectures, inevitably replaced objects. In the words of one reporter, Object teaching was a "verbal drizzle at a small boy holding a dandelion."[5] For these reasons, the Object Lesson idea never attained either wide acceptance or a measure of success.

The nature-study movement

The inevitable revolt against Objects evoked the educational reform referred to as Nature Study. Beginning about 1884, Nature Study, in one guise or another, has remained in existence up to the present. The Nature Study movement is notable because, like Object Lessons, it became an educational fad, much discussed but relatively unsuccessful in infiltrating educational practice. Its spirit, full of Froebelian undertones of interest in and oneness with nature, was distinctly different from that of its predecessor. Liberty Hyde Bailey, one of the leaders in this dissenting science, explained its function in these words:[6]

> Nature-study is a revolt from the teaching of mere science in the elementary grades. In teaching-practice, the work and the methods of the two [science and Nature-study] intergrade . . . and as the high school and college are approached, Nature-study passes into science-teaching, or gives way to it; but the ideals are distinct—they should be contrasted rather than compared. Nature-study is not science. It is not facts. It is spirit. It is concerned with the child's outlook on the world.

Numerous sub-species of Nature Study were advocated, some restricted to biological and earth sciences, others including some physical science; but almost always there was the common denominator of stress on the biological. This was particularly noticeable in the courses outlined for younger children. There were distinctly new overtones of emotion and sentimentality, perhaps because of a massive insistence on the doctrine of interest. Many of the authorities were emphatic in their belief that children must be personally involved in order for real understanding to occur. Their textbooks, therefore, continually stressed the importance of arousing interest. In actual practice, children's interests were identified with those of the textbook writer, or, on more or less hypothetical grounds, with nature, which was assumed to be "near and dear" to children.

There is undoubtedly no "typical" manual which clearly defines

Nature Study. Indeed, dozens of manuals and textbooks were published during the thirty-year period, approximately 1890–1920, in which Nature Study was so vigorously advocated. However, a book written by Mrs. L. L. Wilson, who was an exceedingly well qualified author, is an excellent model to examine. This text, *Nature Study in Elementary Schools*, was reprinted at least nine times following its publication in 1897, and was adopted by many school systems. The four content areas, weather, plants, animals, and "stones," were arranged in a monthly sequence for children in the first four school grades. For obvious reasons, calendar organization was very common in Nature Study manuals. In September, autumn flowers, ferns, insects, weather phenomena and weather records were recommended. In November, the weather record continued, along with an investigation of temperature, the sun and moon, falling leaves, buds, bulbs, fleshy roots, pigeons, cocoons, and the preparation of animals for winter. In March, the weather record was maintained, along with a study of buds, the food supply of seeds, earthworms, birds and bird migration, soil, mica, sand, clay, quartz, feldspar, and pebbles.

Detailed information for utilizing the proper method was included, along with the necessary scientific background. Mrs. Wilson took it for granted that her readers were scientifically unprepared: "The courses generally pursued in college and university do not necessarily equip the student for practical, everyday work with little children."[7] She therefore left little to chance. Her prescription for effective teaching is still apropos. After forewarning teachers to prepare themselves by study of the factual content of her book, she encouraged them in these words:[8]

> *Leisurely* guide the child's observation, imagination, and reason to the most important truths with reference to the subject of the lesson... remember that the object is to lead the children to think. Their untrained minds cannot do this in an atmosphere of impatience, emphasis, and hurry...[the teacher] should not have anxiety to cover a definite ground.

Mrs. Wilson, who focused the attention of children on easily perceived characteristics, encouraged them to answer such questions of function as "How does the earthworm move?" No real attempt was made to elucidate principles; her emphasis was on the primacy of observation as the major source of factual information. Physical science was omitted because she assumed that teachers were more interested and better prepared in the biological and the earth sciences, and that firsthand experiences were more readily available in these sciences. In addition, she believed that the kind of quantitative understanding demanded in the physical sciences was inappropriate for children.

An important characteristic of Nature Study as it evolved was the

Herbartian affirmation of correlation with such studies as drawing, modeling, reading, writing, and music, which often resulted in ridiculously far-fetched combinations. In actual classroom practice, however, teachers, lacking the requisite knowledge, taught mechanically, remorselessly traversing a textbook or manual. The visible outcomes of this kind of instruction were collections of leaves, rocks, insects, and twigs.

Nature Study, at its best, is still a significant force in the teaching of science. Unfortunately, its potentialities for the education of children have seldom been fulfilled. Many men and women struggled valiantly to capitalize on the scientific value of Nature Study. Wilbur Jackman, one of these pioneers, wrote these provocative words when the misteaching of Nature had become evident:[9]

> The spirit of nature-study requires that the pupils be intelligently directed in the study of their immediate environment in its relation to themselves; that there shall be, under the natural stimulus of the desire to know, a constant effort at a rational interpretation of the common things observed... This plan... will lay a sound foundation for the expansive scientific study which gradually creates a world-picture, and at the same time enables the student, by means of the microscope, the dissecting knife, and the alembic, to penetrate intelligently into its minute details.

Nature Study in the elementary schools failed to meet the glowing expectations of its founders. Despite the assurances of Mrs. Wilson and the other writers, it *was* necessary for teachers to know a great deal about nature and the study of nature. Even though the courses were arranged seasonally, the difficulty of obtaining materials was a perennial obstacle. Field trips, recognized for their educational value, were ignored because of administrative and methodological hazards. Perhaps the most effective hindrance lay in the silent resistance by the rank and file of classroom teachers and the vociferous opposition by high school and college teachers of science. One of their spokesmen expressed his antagonism in these words:[10]

> High school teachers of science must protest against a mass of so-called nature study, more or less sentimental and worthless... and must not be content simply with treating lightly this farcical science teaching, or passing it by with silent contempt.

Elementary science

During the Nature Study period, a different school of elementary-science instruction also attained some prominence. At first, as a simplified version of high school science, it was nothing more than textbook recitation which systematically surveyed the sciences and was occasionally punctuated by an exciting demonstration. Hooker's *Child's Book of Nature* and Wells' *Science of Common Things* were among the texts commonly selected for this purpose. They wholeheartedly transferred the organization of the sciences into the elementary curriculum. Like their more sophisticated prototypes, they gave priority to the utilitarian values of scientific laws and principles.

In 1871, William Torrey Harris, then superintendent of schools in St. Louis, published a curriculum in science for the elementary grades which attempted to show how scientific ideas were interrelated. While not the first published elementary-science curriculum, it is notable for its recognition of relationships. Harris, one of America's most influential educational philosophers, relegated the sciences to a role subordinate to the humanities. He assumed that mastery of "the material world" could occur only after social and humanistic principles had been assimilated. "It is more important," he said, "for man to know human nature than material nature. But it is not necessary for him to be ignorant of either."[11]

His curriculum outline, expressed in the concepts and structure of the formal sciences, is well worth reprinting:[12]

> The first year, lowest grade, in the schools began with lessons on the plant; the second year was taken up with animals, and especially the structure of the human body; while the third year initiated the pupil into the physical forces in various familiar applications, and made some progress in considering the geological and meteorological elements, such as earth, air, fire, and water. In the fourth, fifth, and sixth years, the course took a more practical turn. While in the first three years, it had dealt chiefly with the rationale of the child's playthings and such phenomena as excited his astonishment, in the second course he was to learn to understand what is useful to man in these departments. In the sixth and seventh years the maturity of the pupil allows him to investigate with some degree of scientific interest and hence the more general form is adopted.

Although Harris emphasized the factual nature of the sciences, he did group these facts and principles according to their relationships. He resisted the overemphasis on facts. He cautioned his teachers to illustrate the logical development of principles from simple facts and urged them to draw on the background of experience which children possessed. He advised teachers to avoid superficiality by limiting the number of concepts presented. To this end, he devised a three-year teaching cycle to insure some depth of learning.

In the schools, the Harris course of study suffered from the same sterility and rigidity which afflicted Object Lessons and later paralyzed Nature Study. There could be no real difference, because children were left to the verbalizations of the *Child's Book of Nature* or of the other texts which Harris suggested. The hour per week recommended by Dr. Harris was absurdly inadequate for the teaching of even one concept in depth.

Herbartian influences

The rise of Herbartian psychology led to objectives which were directed at generating intelligent social behavior by understanding the child's environment. The goal of practical usefulness was superseded by the goal of good citizenship. It was assumed that the child's interest was best stimulated by well organized ideas which meshed with the child's apperceptive mass. It was axiomatic that "correct" ideas in the "proper" sequence caused the desired behavior to occur. Unfortunately, none of the Herbartians knew what these ideas were, nor how they could be effectively organized. As a result, the texts and methods in elementary science remained essentially the same, a large body of facts that were recited and quickly forgotten.

The big ideas

Many other proposals for the improvement of elementary-science curricula were current during these years of educational ferment. The limitations of space permit discussion of only the few which are still significant.

Wilbur Jackman was particularly influential in building a solid foundation for our present program of science instruction. Jackman's elementary-science curriculum fused an understanding of scientific concepts with a functional grasp of the methods of science. He made scientific generalizations, "the big ideas," his organizational framework, although he did not always state these principles formally. He suggested, for example, that the study of the physical properties of air should be guided by the concept of "energy acting through the atmosphere."[13]

Jackman stressed firsthand observation and experiment. His major work, *Nature Study for the Grammar Grades*, is a series of questions which direct observation, experimentation, and interpretation.[14] Although this book was not the first of its kind, its publication prompted the appearance of several manuals designed to achieve the same ends. None were effective in changing educational practice, but their thesis continues to influence contemporary thought.

The scientific method

As a kind of counterpoint to these proposals, many scientists and educators advanced the notion that understanding of "the scientific method" should be the major goal of science instruction. This Baconian ideal was expressed by such notables as Herbert Spencer and Hermann Helmholtz, who commanded an international audience. Many of the men who were responsible for the education of teachers believed wholeheartedly in its value. The best learning, they said, comes from the application of "the scientific method" to the raw data supplied by experiment and observation. Therefore, the best preparation for life was provided by a scientific curriculum pervaded by "the scientific method." They recognized that rapid expansion of scientific knowledge effectively barred encyclopedic mastery, and that obsolescence was an inevitable result of fact-centered instruction. It was self-evident to these men that children who mastered "the method of science" simultaneously created their own path to continued learning.

In 1895, the National Education Association Committee of Fifteen asserted that science was indispensable in the elementary schools because mastery of scientific method was a key to success in life. This attitude is quite different from the belief that the study of the sciences is the best training for the mental faculties. Indeed, one criticism of Nature Study was that it deliberately suppressed the analytical approach of the sciences in order to inculcate moral and aesthetic values. Nature Study was an attempt to change children's values by confronting them with their world; science, on the other hand, enabled children to change that world.

The advocates of scientific method indulged freely in the educational game of "claim and counter-claim," sometimes overstating their case in polemics as unscientific as those of the Nature faddists. In 1910, for example, John Dewey wrote:[15]

> The future of our civilization, depends upon the widening spread and deepening hold of the scientific habit of mind . . . the problem of problems in our education is therefore to discover how to mature and make effective this scientific habit.

As Chapter 1 points out, this conception of scientific method was somewhat deceptive. Its validity, however, was unimportant, because no concerted effort was made to develop children's ability to think scientifically. Proponents assumed that the mere presentation of the facts of science, accompanied by observation of the objects of nature and by experimental verification of fact, was sufficient to develop the "scientific habit of mind." The growth of laboratory instruction in the secondary schools during the last three decades of the nineteenth century was almost entirely predicated on the belief that the path to mastery of scientific method led directly through the laboratory. The revelation that examining of plant stems through the microscope and collecting oxygen from heated potassium chlorate are insufficient by themselves to foster problem-solving abilities is of recent origin.

Teacher preparation

By 1890, a few of the normal schools which prepared elementary school teachers had incorporated into their curricula exercises in scientific method. They relied on a strangely distorted version of "the method of science," in which students were supplied with brief instructions to "do" something, then commanded to "observe," and finally to "infer" a cause for the observed phenomenon. The technique is aptly illustrated by the experience of one young normal school student whose laboratory task one day was to examine a rusty piece of iron. The observation that the brownish substance covering its surface was iron rust led her to infer that atmospheric oxygen "Unites with iron and forms rust."[16]

This impossible extension of a single observation characterized the "method" manuals written expressly for prospective teachers. Granted that oxygen is a component of the atmosphere, that it is an active chemical element, and that iron rusts when exposed to air, the conclusion that rusting is caused by the union of iron and oxygen is completely unwarranted. This inference is justifiable only after controlled experimentation to isolate the pertinent dependent and independent variables, an analysis of rust to determine its chemical composition, and the experimental proof that the chemically combined oxygen in rust is of atmospheric origin. In the classroom, this version of scientific method failed because students somehow discovered the required information; not, of course, from their own observations and experiments, but from the references with which their manuals were so copiously sprinkled. In short, the pleaders for scientific method in the classroom were themselves almost absurdly guilty of violating their own philosophical tenets.

Teachers who endeavored to teach scientific method were hamstrung by the assumption that experimentation and observation were sufficient. Despite the fact that verification was the sole outcome, students were somehow expected to perfect their understanding of scientific method. By some mystic osmosis, they emerged from elementary-science instruction purified, exalted, and scientifically select, ready to take their places in the new technological society.

The heuristic method

Fortunately, not all who espoused "the scientific method" were so trusting. Henry E. Armstrong, a leading English chemist of the late nineteenth century and a crusader for science in the schools, was convinced that recitation was an abomination. He proposed that children find out for themselves, and devised a "heuristic" method for this purpose. This conception has recently re-emerged as Inquiry or Discovery. Dr. Armstrong pictured the teacher as a guide, a planner of problems for children to investigate, an organizer of the proper conditions for the solution of these problems. As he put it, the heuristic method was nothing more nor less than "placing students as far as possible in the attitude of the discoverer—[using] methods which involve their *finding out* instead of being merely told about things."[17]

This vision of the teacher's role was so different that Armstrong was belabored as a mystic who, by laying out impossible and unimportant tasks for children, was impeding science in the schools. The notion that children were able to plan their own mode of attack on problems was inadmissable in both England and the United States. It was axiomatic that children, because they were children, could learn only with the most rigid of direction.

Armstrong, almost alone, insisted that children should not only *not* know the outcome of their experiment, but that each child ought to be a detective, hunting down the clues (the hunt itself serving as motive), sifting them, and eventually coming to a conclusion of his own. (Bruner's insistence on the importance of shifting from extrinsic to intrinsic motivation is a modern conception of this provocative idea.) Perhaps because of his own superlative scientific talents, he erred by providing too little assistance and by complicating the problems which children encountered with technical difficulties. He was, however, well aware that the laboratory alone could not develop the traits of thinking and the attitudes which he prized. Free discussion and informative lectures were also required. He realized that children could not possibly rediscover all scientific knowledge, and that much of science must be learned in other ways. Again and again, he reiterated the heuristic theme:[18]

> The facts must always be so presented...that the process by which results are obtained is made sufficiently clear as well as the methods by which any conclusions based on the facts are deduced. And before any didactic teaching is entered upon to any considerable extent, a thorough course of heuristic training must have been gone through in order that a full understanding of method may have been arrived at and the power of using it acquired: scientific habits of mind, scientific ways of working, must become ingrained habits from which it is impossible to escape. And

> as a necessary corollary, subjects must be taught in such an order that those which can be treated heuristically shall be mainly attended to in the first instance.

This is how he described his methodology of teaching young children:[19]

> As soon as they can write, children will be required themselves to make out lists of the things they have collected, and as they systematically study these, to note down their origin, colour, and other properties obvious to them. And then they will go on to make experiments to ascertain properties which are not quite obvious. For example, they will be provided with a simple anvil...and with the aid of this, will find out that metals are more or less soft and may be bent and beaten out; that other substances are hard and brittle... Then by measuring and weighing regularly shaped blocks, slabs, or plates of wood, stone or metal, the differences in density of different stuffs will be discovered... Each day let some simple task be set; insist that this be carried out with scrupulous care and equally carefully be recorded in a very few lines of clear simple language.

The Teaching of Scientific Method and Other Papers is profitable reading today. Much of what Armstrong asserted then is fully supported by modern theory in science education. The emphasis on individual activity, self-motivation, and genuine "research" is noteworthy. Armstrong was truly far-seeing. He made no impression in the United States, and hardly more than a disturbance in England, but the fresh note he struck in the education of children has magically survived as a summons to reform of elementary-science teaching today.

A study in futility

The reams of printed courses of study, textbooks, manuals, and periodical pages which poured from the presses during the nineteenth and early twentieth centuries were perhaps not wasted, but they were futile. The national debate which compared Elementary Science with Nature Study (the names were often interchangeable) was a battle of ill-winds with no anchor to reality. Neither program was functional. Teachers continued to teach what they had been taught—arithmetic, geography, reading, and writing—by the time-honored, although universally detested, dry rot of recitation and drill. Undoubtedly those teachers who were devoted professionals, idealistically aware of their responsibilities, capitalized on the Froebelian and Herbartian themes of the nature of the child, interest, apperceptive mass, and correlation. But few broadened the study of fundamentals to include the sciences, and fewer still taught science in accord with the best ideas of their times.

Commentators attributed this scientific vacuum to the lack of interest in science by teachers who characteristically knew little science and who were therefore fearful and insecure. It is a matter of record that little or no equipment for teaching experimental science existed in the schools. There were, it is true, some excellent manuals which required the simplest of home-made equipment, but they seem to have been almost unused. Even Nature Study, which required nothing more than some specimens from the out-of-doors, or as little as a clear view of the sky, was as likely to be neglected as were the physical sciences.

Revival of elementary science

Nature Study continued to dominate elementary school science curricula well into the twentieth century. It faded from the scene only when a new generation of dedicated reformers came to positions of national influence. Such men as Samuel Powers and Gerald Craig at Teachers College, Columbia University, fought to revive Elementary Science, which to them was a systematic, conceptually organized, integrated program embracing all aspects of physical, earth, and biological science. Their missionary zeal was so effective that by 1940 it was difficult to locate a school system in which Nature Study was said to be taught.

The major source for the structure of contemporary elementary-science programs is the work of Gerald S. Craig, who, in 1927, published the single most influential research in elementary-science curriculum construction. Craig analyzed hundreds of textbooks, courses of study, and journal articles in order to derive a long list of important scientific ideas. Each idea was rated by a panel of educated laymen for its importance for children. Craig's principal criterion for rating was that each idea must be sufficiently powerful, when understood, to modify both the thought patterns of children and thought in other fields of knowledge.[20] These ratings were then compared with the frequency with which the same principles appeared in thousands of children's questions which Craig had systematically collected. From these data, Craig proposed a large number of generalizations, laws, principles, and concepts as the core of the elementary-science curriculum.

It is interesting to note that few of the ideas thought to be important by adults were represented in any substantial way by children's reported interests. Indeed, the role of scientific knowledge in maintaining health, a principle that headed the laymen's list, ranked forty-ninth in the children's list of fifty. Adults were obviously motivated by the social usefulness of scientific concepts and by the constructs of science. Children, on the other hand, were predominantly environment-oriented.

Many lists of principles have since been published, some of which place these principles at specific grade levels. But, because placement has been more or less arbitrary, it has also been singularly unsuccessful. There is *no agreement* on the proper age at which to introduce such important principles as "The earth is very old," or "Green plants make food by means of the process of photosynthesis." A cursory study of textbooks and courses of study quickly reveals how confusing and confused is the assignment of principles by age. And little improvement is likely in the near future, although research on cognitive structure and the intellectual maturation of children will eventually provide a sound foundation for placement.

In 1932, Dr. Craig published a series of graded elementary textbooks which embodied his research. This series, the direct ancestor of the many now available, was structured on a framework of empirically distributed principles. Craig tried to provide a continuous and integrated curriculum by means of cyclical framework and by interrelated content units. Unfortunately, few teachers were able to utilize these books as Craig intended, in part because of text limitations, in part because science teaching requires superior teacher training and experience. Indeed, the many problems which Dr. Craig attempted to surmount several decades ago are still very much in evidence.

The thirty-first yearbook

In 1932, a committee of prominent science educators provided in the thirty-first yearbook of the National Society for the Study of Education an authoritative restatement of Craig's curricular research. Their reaffirmation of the potential of the "big idea" was instrumental in its adoption by prominent textbook and curriculum writers. Their point of view was that desirable "life enrichment" arose from the "functional" understanding of scientific principles. The committee defined "functional" as the capacity of the child to associate his own relevant experience with these principles and to apply them to new but related experience.[21] Curriculum, therefore, consisted of the relevant readings, experiments, demonstrations, and other activities which jointly created "functional" understanding.

In essence, these curriculum reformers were striving to incorporate the same "structure of science" which still excites educators today. The centering of curriculum on principles presumably decompartmentalized the traditional distinctions between the sciences, because the selected principles were universal in their scope. A generalization such as "the environment acts upon living things, and living things upon the environment" obviously impinges deeply on the chemical, physical, and earth sciences.

In the classroom, however, the study of generalizations for their own sake converted a well-planned and potentially valuable design into a travesty. The power of scientific principles to elucidate the complexities of nature, to predict physical phenomena, and to affect social life was never clearly understood by many teachers. The principles approach has failed to produce any substantial agreement in the organization of curriculum materials. Many texts and courses of study are arbitrarily divided into units with such titles as "The Earth's Changing Surface," "Life in the Past," "Machines," and "Aviation." In accord with sound practice, their content is drawn from environmental phenomena which are explained by the relevant principles. Unfortunately, these units are often trivial, and, notwithstanding the implied integration of the unit organization, tend to converge on the assimilation of facts.

Some texts, particularly those prepared for younger children, resort to much narrower centers of interest, such as "Grasshoppers," "Eggs," and "Trees." Their dependence on Nature Study is evident. Indeed, there is still an overemphasis on descriptive biology, which is only partly mitigated by the incorporation of physical science in the intermediate grades. The idea that biological events and their associated concepts are more easily comprehended by children than are the principles of the physical sciences is unsupported by the available evidence. Despite this, the same rationalizations proposed for the dominant role of biology in Nature Study are clearly evident in elementary science today.

A modern textbook

The content and organization of elementary-science textbook series are best illustrated by analysis of one of the leaders in the field.[22] This series is impressively organized, and its potential for improving the quality of science teaching is obvious. Its ten areas, which are listed below, include all of the sciences; each, with a few exceptions, is taught in every grade, with varying emphasis from grade to grade.

Major Areas

1. Health and Nutrition
2. Living Things
3. Conservation, Balance of Nature
4. Rocks and Soil

5. Atmosphere and Weather
6. Chemical and Physical Change
7. Motion, Mechanics, and Technology
8. Electricity, Magnetism, and Gravity
9. Energy from the Sun
10. Earth and Sky

Three areas are mainly biological, three are drawn from the earth sciences, and four are drawn from the physical sciences. A carefully planned repetition of scientific terms, concepts, and principles supplies an integrating mechanism. As an illustration of this planning, Book 3 presents such concepts as air pressure, atmospheric change in volume resulting from temperature change, condensation of water vapor, sound waves in air, and the oxygen content of the atmosphere. Book 4 adds the concepts of physical change, states of matter, melting point, evaporation, and freezing point. Book 5 describes the gaseous composition of the atmosphere, convection currents, and changes in the rate of evaporation of liquids.

The content of the "Chemical and Physical Change" area reiterates and strengthens these concepts by introducing them in different contexts. For example, Book 2 begins the study of the thermometer and of temperature change. This is followed in Book 4 by abstract notions of states of matter, molecular motion, atomic and molecular structure, physical change, the role of oxygen in combustion, and chemical change.

The texts are copiously illustrated with challenging pictures which are intimately coupled with the written matter. The authors have earnestly tried to translate the goals of science education into practicable, achievable activities. They transcend the presentation of subject matter for its own sake by including many exercises which stimulate the child's creative imagination and enlarge his capacity to examine ideas critically. Their questions, more often than not, cannot be answered by mere repetition of the printed word. The authors do, indeed, strive to guide children to grow in understanding the structure of science by coordinating fact with concept and by raising questions which may be answered only when the unifying concepts have been mastered. Their *Teacher's Guide* is a minutely detailed source book for effective exploitation of the textbook. This series will undoubtedly enrich science teaching in the hands of the conventionally trained teacher.

Many of the other textbook series are similarly patterned. They are written for the elementary schools by experienced science educators and classroom teachers, and, in their own terms, are truly on a high level. They share, however, in the weakness of curriculum rigidity. The design of science curricula depends to a large extent on informed opinion, because valid research with children, which alone can provide the proper psychological foundation, is not yet sufficient of itself. This does not imply that there is no substantial research on the thought processes of children and on their cognitive growth, but rather that much of this research has not yet been translated into a serviceable guide for the grade placement of scientific concepts and principles.

The rigid curriculum and the textbook

The dilemma which originates with the rigid curriculum is not easily escaped. The mobility of contemporary American life assembles children of surprisingly heterogeneous scholarship in the classroom. Curriculum planning, no matter how finished in principle, is ineffective in coping with these differences. Every teacher expects a number of her pupils to be inferior readers, for example—a circumstance which creates difficulties because of the customary centrality of the text in her science teaching. Other children are unjustifiably retarded because the schools from which they come have adopted a different series of textbooks. Consequently, few children at any *one* grade level have a common background in science.

Unless the system of education in the United States becomes highly centralized and therefore standardized, this quagmire of diversity will continue to plague us. For this reason, if for no other, the national and regional curriculum planning represented by textbook series and by courses of study cannot function effectively. The detailed kindergarten to twelfth grade program of science instruction which is so widely advocated can only operate efficiently in a society vastly different from our own. The textbook, by its very existence, tends to nullify the operational understanding of the process of science, codifying science as a body of knowledge despite the best efforts of its authors. In the hands of the unwary teacher, it may become a series of reading lessons in which the illustrations take the place of first-hand experience.

Another related weakness of some texts for the new science education arises from their dogmatic presentation of firsthand experience. Their activities are written to corroborate a statement in the book. For example, children may be directed to perform a minutely detailed "experiment" to verify the generalization that "heat causes metals to expand." The illustration which accompanies the directions all too often provides the answer, so that children are deprived of the anticipation of finding out for themselves. Children undoubtedly enjoy this experience, but its educational value is questionable. Textbooks rarely provide situations which lead naturally into cooperative planning or which give the teacher the opportunity to evaluate growth in ability to propose hypotheses, gather data, measure, compare, infer, and generalize.

Certainly, textbooks and their variants are not *all* bad. Good texts, such as the series previously described, can be used intelligently and effectively by teachers who are aware of the weaknesses described above. There is, however, justifiable doubt about the extent of true learning of scientific principles which comes with text-based teaching, just as there is little reason to assume that many textbooks promote understanding of the scientific process. A sound case, however, may be made for increased reliance on authoritative presentation of facts and explanations as children grow in ability to think formally; as they are better able to deal with multiple variables on a semi-abstract level, and as their knowledge of the world expands.[23]

Economy of time and of thought is a sufficient reason for deriving a large part of secondary school science learning from expert sources. The situation is quite different in the elementary school. This is the time for children who are intensely curious, and for whom vocational preparation and the content of the individual disciplines are of little concern, to approach science as inquirers, as discoverers. The tasks of finding out what, why, when, and how, without insisting on the memorization of facts and generalizations, are in themselves worthy goals for these children.

At best, a textbook is a tool; no text, despite the excellence of its accompanying teacher's manual, can achieve its postulated aims unless teachers are sympathetic to these aims and determined to achieve them. In practice, therefore, textbooks are often stultifying, limiting, and inflexible.

The unit book

In an effort to minimize dependence on a textbook, schools frequently provide multiple copies of several different texts in each classroom. Books thus may become a kind of resource from which teachers and students may extract pertinent information. This approach is useful if instruction is focused on problems arising from cooperative teacher-pupil planning. Unhappily, textbooks are rarely complete enough to supply information in depth, or to direct children to the proper sources. Such questions as "If the Earth has gravity, why doesn't the Moon fall?" or "How do we know that everything is made up of molecules?" are likely to be unanswered in the text because it is not its function to anticipate such questions. Texts are not designed to serve as scientific compendiums, but rather to supply a carefully selected minimum core of scientific facts and principles for classroom instruction.

Publishers who recognize the inherent inflexibility of the textbook have prepared paperbound "resource" pamphlets which treat individually and in depth such topics as weather, animals, the planets, and machines. Some publishers bind each textbook unit separately so that a selection of appropriate units may be made. The obvious methodological advantages are balanced by concomitant disadvantages. Multiple copies of these unit books are more expensive than a single set of books: they are also less resistant to normal wear and tear. But, in addition, if a unit book purposefully integrates concepts first presented in another volume, the difficulty of learning is inevitably increased because these concepts are assumed to be part of the learner's experience. In an attempt to avoid this outcome, short recapitulations of important ideas are often provided, either at the beginning of the unit book, or at strategic intervals. These summaries merely reemphasize the devotion of textbooks to the "rhetoric of conclusion." A two-hundred-word explanation of the electronic structure of the atom interpolated into a unit on static electricity is a conceptual roadblock of some magnitude.

The growth of genuine understanding of static electricity, or of any other complex phenomenon, is time-consuming and unlikely to be stimulated by brief outlines. Surely, even the traditional model of atomic structure deserves a better fate than its acceptance as dogma. Ought not children to have the opportunity to become familiar with scientific models and the justification for accepting this particular atomic model? Is it not possible for intermediate grade children to discover by experiment, demonstration, animated film, and inductive reasoning why scientists propose such conceptual schemes? Only youngsters who are fortunate enough to experience this kind of teaching will profit from the two-hundred-word summary of atomic structure. A summary of atomic structure then makes a meaningful contribution to the unit on static electricity.

The fact-centered curriculum

All too often, the textbook is studied from beginning to end; the children participate actively in all the demonstrations and experiences suggested, but the outcome is "almost entirely in facts rather than process... The purpose of these experiments... is always to prove a fact, which is *not* the point of scientific inquiry."[24] This fact-dominated curriculum is astringently summarized by one critic in these words:[25]

> Throughout their school career, children prove that beans grow higher in fertilized soil than in unfertilized soil, that a metal police badge placed between the poles of a switch will make an electric bell ring while a plastic police badge will not, that a piece of lead falls to the bottom of a glass of water while a piece of wood floats on top, that mercury rises in a thermometer when the bulb is heated. Once the fact is proved, school science

> is through with it, and unless the child has the luck of an extraordinary teacher he cannot learn in school that a fact is merely a beginning, that there are always questions of causation, of condition, of verification, of prediction by analogy. School science simply presents a hypothesis and a recipe for an experiment which will 'prove' it, and then the books are closed and we can all move on to something else, thank God. It is hard to find the right word for this procedure; 'fraud' seems too strong because it implies intent, and everyone's intentions are honest. But its results are decidedly fraudulent.

It is not unusual to find a description of controlled experiments. But it is novel to discover suggestions by which such experiments may be carried out or outlines of multiple probes by which to obtain valid, generalizable data. Explanations of the kind described in Chapter 1 of this book are almost never encountered. The implications of experimentation, the limitations of knowledge, and the tentative nature of much that we know are ignored. Is it any wonder that the "cultivation of inquiring minds," so eloquently described by Laura Zirbes, is still but a rhetorical phrase?[26]

The interest-centered curriculum

Science has often been taught incidentally. In incidental teaching, the immediate interests of the class generate content. For example, the resourceful teacher is quick to draw upon a butterfly brought into class, either as subject matter for a brief lesson on butterflies, or as a point of departure for a comprehensive unit on insect life. Such teaching, however, is fraught with complexities of commission and omission. Significant areas of science are often overlooked, or, on the other hand, overtaught. The major problem arising from this narrow environmental approach is that the potential for a valuable learning experience is insufficiently realized because time for planning and preparation is unavailable. The mere exhibition of the butterfly, with perhaps a hasty glance at its parts and a verbalization that the butterfly is an insect with complete metamorphosis, cheats both children and teacher. The opportunity to learn how the butterfly is adapted to its ecological niche and how scientists study butterflies is never seized. Our indictment is perhaps unfair, but teaching of this kind has not been uncommon.

Curricula which are structured around the expressed interests of children are unsound because these interests are notoriously unstable. It may be laboring the point to remind the reader that children tend to be interested in those aspects of science which they know or which are sufficiently bizarre or unusual to be inherently fascinating. The lively curiosity which children manifest about the life history of prehistoric animals is a case in point. Few girls, on the other hand, are anxious to know about machines, familiar or unfamiliar, nor are they ordinarily concerned with operational principles. Interest, of itself, is too weak a prop for the science curriculum, although the master teacher is astutely successful both in capitalizing on interest and in arousing interest in unfamiliar phenomena. Methodology and content do not create a master teacher of science; the master teacher reshapes and reconstructs methodology and content to suit his own educational purposes and strengths.

Summary

The teaching of science in the elementary schools has had a long and exciting evolution. Its early proponents advanced the notion that science was peculiarly suitable for enhancing the theological, utilitarian, and disciplinary goals of nineteenth century education. Before the nineteenth century ended, however, these goals had shifted to mastery of "the scientific method" and appreciation of "nature."

The purposes which underlie contemporary science education include competence in "problem solving," which is closely related to "the scientific method" of earlier years, as well as understanding of certain important generalizations which can change the learner's behavior patterns. In keeping with this progression of educational purpose, educators have moved from one curricular panacea to another. The dependence on textbook recitation a century ago was converted to the "verbal drizzle" of Object Lessons, which, in turn, succumbed to the emotional blandishments of Nature Study. A dissident group of educators argued vigorously for a structure which prepared children to think "scientifically."

During the decade of the '30's, the "big ideas" of the sciences emerged as the dominant content and methodology of contemporary elementary science. However, this relatively inflexible curriculum is now changing to an Inquiry-centered methodology in which process is more important than product.

Despite the almost kaleidoscopic fluctuations which mark the evolution of elementary science, actual classroom instruction in science has been relatively rare. When taught, science has almost always been in the form of textbook recitation. The educational propaganda of each era seems to exert a negligible effect in the classroom. The centrality of the textbook is almost as pervasive today, when science is accepted in many elementary classrooms, as it was in the poverty-stricken one-room schools of our distant past.

It is unwise to disregard the potential of curriculum guides, syllabi, textbooks, and manuals as instruments for effective teaching of elementary science. Their time-tested activities ease the struggles of the eager, conscientious teacher, who looks to them for suggestions instead of prescriptions. In accord with the philosophy of this book, we recommend that teachers utilize commercially published texts as sources of data and explanations which are otherwise unobtainable from either firsthand experience or other vicarious means. It is unfortunate that few textbooks meet these criteria, and therefore, that Inquiry-centered instruction is unlikely to flourish when tied to texts. Textbooks are conservative, perhaps because of their users. The routine, the security of knowing exactly what materials are required and what answers are expected, may make for heavy sales. But it also inhibits the exciting investigation of the world of science.

For further study

1. Contrast the aims of elementary school science one hundred years ago with those of contemporary elementary-science education.
2. How have elementary-science objectives changed because of changing conceptions of the child, society, and technology?
3. How has the goal of mental discipline been transmuted in modern education?
4. Contrast the purposes and outcomes of Nature Study, Object Lessons, and the early Elementary-Science movement.
5. What reasons can you suggest for advocating "the scientific method" as the mode of teaching elementary school science? Is belief in "the scientific method" justifiable as a way of analyzing the world?
6. How does Armstrong's "heuristic" method differ from other proposals for teaching elementary science?
7. Examine a series of contemporary elementary-science textbooks in order to discover the extent of their dependence on Craig's curriculum proposals of 1932.
8. Trace the evolution of curriculum ideas in the National Society for the Study of Education yearbooks of 1932, Part I; 1947, Part I; and 1959, Part I.
9. Write a critique of an elementary-science textbook series that deals with its adequacy for meeting the demands of contemporary science instruction.
10. Are the authors justified in their comments about the relationship between textbooks and the rigid curriculum?
11. What are the alternatives to a curriculum which is centered on the textbook?

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Few elementary-science textbooks and fewer "experiment" manuals omit this simple experience: The child is directed to fill a glass with water and to cover the glass with an index card. Then, with the card carefully pressed on the glass, the child slowly inverts the glass (over the sink), removes his hand, and lo! the card adheres firmly to the glass. Contrary to expectation, the water obstinately remains in the glass. It is startling (particularly if it is carelessly performed), but the excitement fades quickly as the experience is explained by this line of reasoning:

The water remains in the glass because the pressure of air pushing up on the card is greater than the pressure of water in the glass on the card, and therefore the card is forced tightly against the glass and seals it. This is probably how you would explain why the water remains in the glass. How would a child explain this phenomenon if, as is likely, his understanding of air pressure and fluid phenomena is extremely limited? Would he not say that "the paper sticks to the water" or "the water can't fall out—the card covers the glass" or, more probably, "I don't know why. I can't figure it out." If the conceptual structure of the child encompasses equilibrium of forces, he may reply that the water remains in the glass because the forces pushing up must be equal to that pushing down. This response, however, is too sophisticated for a child who is not science-oriented. Children who can propose equality of forces without a supporting framework of experience-derived pressure and force concepts are found in few classrooms.

4

Inquiry and its corollaries

As conventionally and historically presented, the glass-and-card experience is merely a convenient, interest-arousing visual aid for informing the child that air pressure is exerted both up and down and, by implication, that fluids also exert pressure up and down. The learner is hastily informed that the card prevents the water from falling out because the upward pressure of air is sufficiently great to overcome the weight of the water in the glass. This experience is verificatory; that is, it supplies a visual demonstration of the principle that fluids exert pressure up as well as down. The addition to the child's conceptual structure is insignificant, because at no time does he understand the vocabulary, the assumptions, or the implications of what he sees. If verification is the main purpose of this experience, then it is wise for the teacher to abandon it, time-hallowed though it is, and seek a more fruitful center of study. But verification need *not* be its sole function. There is much more to a glass of water and a card than is apparent. Suppose that the teacher demonstrates this experience, but, prior to inverting the card and glass, asks the class what they think will happen and why it will happen. The expected response (if only to be contrary) is that the water will stay in the glass, but there will be few explanations. The teacher may then suggest that the class find out by referring to their textbooks or to other sources. The teacher accepts the "authoritative" explanation, writing it for all to see on the blackboard. She changes the conditions slightly in order to see whether or not the explanation is still valid. She pulls the card down slightly (very carefully) without spilling the water. She asks the children to look closely at the interface between the glass and the card. They see that the card does not press against the glass; that there is, indeed, no direct contact between card and glass, and that a film of water extends around the rim of the glass. She then asks if the earlier explanation is completely correct. How is it possible for water to remain suspended in the glass if the card no longer seats tightly against the glass? She then moistens a card and applies it to a wet, empty (really empty?) glass once more. Does the card still adhere to the glass? What keeps it on? Is air pushing on it? At this point, some children may guess that the set card sticks to the glass, and that the push of air has nothing to do with its adhesion. Can this be tested? Will a dry card adhere? Will a card covered with waxed paper adhere? Will the waxed card adhere to a glass filled with water? Is waxed paper wet by water? If not, must the card be wet before water is retained in the glass? Will the card adhere if the glass rim is lightly coated with oil?

By this time, many members of the class should have arrived at the notion that the card remains in place only as long as it is wet, and that the water "connects" the glass and the card. Is it possible to carry out this experience with materials which are not wet by water? If suitable materials are not suggested by the class, the teacher may use a polyethylene bottle (baby bottle, for example) and a polyethylene cover (freezer container cover). The results are enlightening. Is it possible that air pushes up only if a water-wettable cover is used?

Let the teacher vary the original demonstration by filling the glass only half full. The card still adheres. In the first case, the card adhered because the pressure of the atmosphere pushing up was said to be at least equal to the pressure of water pushing down. But in the second case (the partly filled container) the space above the water in the glass is presumably filled with air (how can this be shown?), and the pressure on the card within the glass should be equal to the pressure of the contained air plus the pressure of the water. The total pressure on the glass is now greater than the pressure outside, and yet the card remains fixed. Can we still maintain that external atmospheric pressure is sufficient to maintain the card in place? Or is it possible that air pressure in the bottle drops sufficiently to create a partial vacuum? What will happen if the closed end of the container is much larger or smaller in diameter than the end covered with the card? If the container is filled to different heights? The results are surprising and should lead to some doubts as to the accuracy of the textbook answer. For the present, this experience is merely sketched in, and to describe it in detail, to follow its ramifications, is beyond the scope of this chapter.

On the basis of these simple classroom activities, the class should now be able to decide that the "sticking" force of the water between the card and the glass must exert some effect. This answer, so briefly sketched, is more honest, pertinent, and functional than the explanation which is usually given. Furthermore, it arises from a process of Inquiry, which questions the obvious and, by relying on experimental investigation, puts authoritative answers to the test.

Few experiences described in elementary-science manuals are as vulnerable to criticism as this one. But, all too frequently, even those experiences which are scientifically valid are pedagogically questionable, in that children are expected to accept a badly stated inference or conclusion. The same facts can be derived by the children *themselves* as they utilize the methods of practicing scientists in learning scientific facts and principles.

Of course, the elementary-science textbook or "experiment" manual may embed the activity in an elaborate conceptual framework, and thus promote growth in mastering the product component of science, although not necessarily its process. Experimental validity is a necessary but not a unique condition for good science teaching. Indeed, the content of the sciences, of itself, can never be the growing edge of the new science education, no matter how many times that content is revised and up-dated. The new physics, the new chemistry, and the new biology may be taught, indeed have been taught, as dogmatically as their predecessors. Neither memorization of the structure and function of DNA and ATP in biology nor verbalization of the terms "molecules" and "pressure" are reliable signs that the student knows what is meant by these terms and can apply them in different contexts. The goals of science teaching will not be better served by traditional modes of teaching new content. Neither increased rigor nor greater demands on the student will automatically result in more and better learning. Curricular changes must also be accomplished by changes in the spirit, methodology, and goals sought by instructors at all grade levels.

We believe that the most pervasive goal of science education in the elementary schools is the enhancement of the searching, inquiring, rational mind. The evidence is incontestable that elementary-science curricula, textbooks, and teachers have neglected science as an Inquiry process and have consequently vitiated those dynamic components of science which are the essence of scientific progress. American science education has too often substituted the letter of science for its spirit, conclusions for its inquiries.

Fortunately, impressive studies now under way are seeking new and better ways of teaching science. A variety of names have been coined in the attempt to describe the complex methodologies employed. Such terms as "enquiry," "Inquiry," "discovery," "problem-solving," "scientific thinking," and "heuristics" have been proposed. The unifying thread is their dependence on seeking evidence for the solution of some simple scientific question by student activity. Guided by the teacher, children generalize these data into conceptual schemes which lead to new, fruitful understanding. Of course, Inquiry is not new. Many scientists and science educators have long advocated the doctrine that science must be studied by the activities and thought processes of practicing scientists. But it is only in recent years that the effort to learn how children think and how science may be most effectively taught to children has been vigorously and effectively financed.

The authors define *Inquiry teaching as that teaching by which teachers and children study scientific phenomena with the approach and the spirit of the scientist.* We also define science Inquiry in operational terms; it is learning in which these instructional characteristics are consistently present:

1. Scientific processes such as observing, measuring, estimating, predicting, comparing, classifying, experimenting, communicating, inferring, analyzing, and drawing out inductions are habitually employed by children and teachers.

2. Time is unimportant. There is no urgency to complete a topic in order to meet a deadline.
3. The answers sought are not known in advance to children. Not only are these answers *not* often found in textbooks, but textbooks and manuals are chosen because they ask questions and suggest ways of finding answers, but do not *give* answers.
4. Children are genuinely interested in finding solutions.
5. The content of the inquiry is not necessarily related to that which precedes or follows, although in some of the new elementary-science curricula (*Science—A Process Approach*, for example) each activity is directly connected with prior and future learning.
6. Teaching and learning are "Why?" centered. Questions such as "How do we know?" "Are we justified in this assumption?" and "Are we justified in this conclusion?" are characteristic of the Inquiry style.
7. A problem of some kind is identified and narrowed until it seems probable that it can be solved by the class.
8. Hypotheses are proposed by the class in order to guide the investigation.
9. Children take the responsibility for proposing ways of gathering the data from controlled experimentation, observation, reading, and other pertinent sources.
10. These proposals for action are cooperatively evaluated. Pertinent assumptions, limitations, and difficulties are identified whenever possible.
11. Children investigate in small groups, as a class, and as individuals in order to gather the data by which to test the hypotheses.
12. Children summarize their data and come to tentative conclusions about the adequacy of their hypotheses. Every effort is made to formulate scientific explanations.
13. Conclusions and explanations are incorporated whenever possible into the great guiding themes of the sciences.

Inquiry is not restricted to the laboratory or to observation, nor is its success guaranteed. Children must become aware of the difficulties, the doubts, the false starts, and the grueling labor involved in thinking up new ideas, ideas which are soon altered and perhaps completely discarded. Children can learn *how* scientists learn, and in the process, "learn" science. It is feasible for teachers to stress the "Why's" and the "How do you know's." They can provide opportunities for practicing how to phrase answerable questions, for isolating problems, inventing workable hypotheses, and for deriving from data the simplest possible principles. In short, the goal of Inquiry teaching is not merely to understand the role of science in technological innovation, nor to better comprehend the scientific basis of our world, but to foster the child's ability to speak the language of science through cognition of its structure.

Special values of Inquiry

Many science educators believe that Inquiry, in one form or another, is the most promising approach to the unification of the process and product components of science in the schools. This is a bold, perhaps overoptimistic statement. Surely the history of previous educational panaceas is a warning that rhetoric, isolated from and unrelated to existing conditions in the schools, is insufficient. Therefore, what is the promise of Inquiry teaching which makes the attempt worthwhile? How do the procedures and materials of Inquiry differ from textbook science, from the "rhetoric of conclusion" described in Chapter 3, on which our children have been nourished?

In addition to philosophical and pedagogical reasons for stressing Inquiry, there are a number of psychological, child-centered values. (See also Chapter 2, pp. 97–98.) The eminent psychologist Jerome Bruner proposes four major outcomes of discovery (Inquiry) teaching, even though the experimental evidence for their validity in the schools is not yet very strong.[1]

Outcomes of Discovery Teaching

1. It increases the intellectual potency of the learner.
2. The learner shifts from dependence on extrinsic to intrinsic rewards.
3. Mastery of the heuristics of discovery enhances its transfer value.
4. Learning by discovery expedites memory processing.

Intellectual potency increases because students not only organize study procedures in order to discover relationships but also learn in ways which facilitate assimilation of data in general problem solving. The student who discovers that water expands when it freezes, and who formalizes this relationship implicitly or explicitly, is better prepared to find out why ice floats on water or why a bottle filled with water cracks when the water freezes. The child who is aware of air pressure, equilibrium of force, and surface tension is in a stronger position to apply these concepts if they have been integrated into his own intellectual patterns.

Autonomous reward arises from confidence in one's ability to discover. That is, mastery becomes "inner-directed." It is a truism that demonstrated success imparts confidence in one's own ability. The child who successfully generalizes from his own observations and manipulations learns that he is able to predict certain consequences of his discoveries.

and, in a limited way, is able to control his own environment. At some stage in every normal child's growth, there is a period of intense curiosity, of desire to find out, and this time, for younger children, is a magnificent opportunity for the discovery of autonomous reward. There is in learning a joy, an intellectual happiness, which many children (and adults) never experience, because their learning has been a mechanical regurgitation of predigested pap. Their learning experiences were never planned to provide the reinforcement which originates in the thrill and satisfaction of discovery.

Transfer value arises from the belief that the child strengthens his capacity to pursue Inquiry only by participating in Inquiry. He learns best how to phrase answerable questions by trying to phrase answerable questions. He develops a feeling for the significance of variables by testing variables for relevance. Indeed, it appears to be possible for children to develop an Inquiry "style" in somewhat the same way in which children become so adept at "Twenty Questions." This is not transfer in the older disciplinary sense, which supposedly helped the student of Latin to write better English—that is, the sheer labor of translating Latin was believed somehow alchemically to transform and improve the student in all his intellectual endeavors. Neither is it strengthening common elements such as vocabulary, quantitative skills, or scientific principles in new contexts. It is mastery of a scheme of attack, of an analytical approach which, more than subject matter, is the trademark of the scientist.

Expediting memory processing means a recognition of the probability that the more children are encouraged to organize their learning in conceptual structures of their own devising, the greater is the probability that they can quickly and effectively retrieve that learning. "Learning by doing," a bromide of traditional educational psychology, is basic to discovery learning. Young children in particular must rely on concrete experience as the base for conceptualization—a base from which there arises an increased probability of later retrieval. This is not to deny the importance of accepting much encapsulated, predigested information, but it is much more likely that children will make better use of their own painfully acquired learning because it is their own.

The evidence is not certain—indeed, in the psychological domain, there is little which is absolutely certain. There are *no* experimental results which of themselves are convincing, which demonstrate once and for all that Teacher X can develop desirable abilities in children by means of discovery techniques. There is good reason to be optimistic, however, if children are drawn into simple scientific problems which are presented through concrete experiences. The difficult vocabulary and symbolic structure with which children cannot grapple must be discarded, but it is less important than the growth of a spirit of willingness and readiness to find out for themselves. If elementary school science is to cultivate "the Inquiring Mind," it is obvious that each elementary school teacher must face up to the task of strengthening the child's competence in recognizing and solving simple scientific problems.

Although learning by imitation is not impossible, and indeed it is necessary in many academic experiences, the quest for this kind of competence is hopeless if it is book-bound. On the other hand, it is reasonable to believe that teachers who themselves learn science heuristically are prepared to guide their pupils through the pitfalls of illogical reasoning and invalid experimentation and can skirt the routine of rote recitation which has long vitiated science teaching. Children will learn to think scientifically and critically if their teachers both exemplify it *and* demand it of them in daily classroom activities.

That the millennium is not immediately at hand is obvious. Authorities seeking changes in instructional patterns are rarely able to guarantee positive results for their educational prescriptions, particularly if teachers are not sufficiently prepared. It is quite clear, however, that teachers do not often exemplify Inquiry, nor do they customarily demand this kind of thinking in their classrooms. The literature of science education has sufficiently documented the degree to which many teachers neglect the application of investigative skills in isolating, clarifying, and solving scientific problems.

Many widely known educational schemes of the past, such as Progressive Education, Object Lessons, the Contract Plan, and the Morrisson Unit, were based on more or less valid pedagogical theories and were often successful in causing desirable behavior changes in the hands of ardent and skilled proponents of these plans. Unfortunately, these programs were insufficiently tested before they were widely publicized, and it was therefore impossible to estimate their probability of success in actual classroom practice. Inquiry methods have *not* been adequately tested at the present time. Every educator is aware of the functional outcomes of the time-tested question-and-answer methodology which pervades many elementary and high school classrooms throughout the land. He knows, or thinks he knows, the relative degree of success which is attainable by skilled and unskilled teachers, by bright and slow children, and by schools with good facilities and with inadequate facilities. These rule-of-thumb, empirical data for Inquiry teaching are not known.

Considerable data from Inquiry research in many elementary schools have not been accumulated. At present, investigators do not know the extent to which the "average" classroom teacher can use a non-routine, time-consuming procedure whose outcomes are difficult to evalute. But whatever happens in the classroom as a result of these ideas, there will be little loss in either the net amount of science learned by children or in the extent to which they attain the other goals of classroom science. Conversely, there may well be an improvement in overall science achievement. Therefore, there must be no retrogression in the struggle to achieve goals which both science educators and scientists believe are essential. Teachers have *nothing* to lose but the chains of rote instruction which bind elementary science to the nineteenth century.

Development of suitable attitudes

The methodology of Inquiry is almost as strange and difficult for older children as it is for their teachers—neither have been trained in its procedures, nor have they had successful experience with it. But younger children frequently learn by Inquiry, albeit a crude, trial-and-error version which by virtue of its difficulty and relative lack of success (accompanied by an eternity of formal instruction in and out of school) is soon forgotten. Younger children spontaneously ask, "Why does the water bubble around in the bathtub when it's going out?" and "Why does my little metal car sink in the water?" There are frequent opportunities in the nursery school years to introduce children to the joys of resolving simple questions by means of scientific procedures. Young children overwhelm us with their questions, their insights, and their desire to learn, but their interests are frequently diverted into play or fantasy. A teacher who is sensitive to the implications of their interests may channel these interests into an investigation of pertinent phenomena, in order to elucidate relationships of which the children are unaware. The experienced teacher is skilled in guiding the questions and the feedback of answers from a group of children into productive exploration. Each question answered, each interest satisfied, should ideally open a door to new questions and new interests, in much the same way that the research scientist finds that his field of research ramifies as he learns more about it.

Success in Inquiry depends on continual training in the skills and habits of observation, of experimentation, and of inductive and deductive thinking. The content selected (usually, in a formal teaching situation, by the teacher) must be of sufficient interest to present a problem, not a puzzle, to the learner. It must also be appropriate for the application of those habits which collectively are labeled "Inquiry." It is redundant to say that children are motivated to pursue Inquiry if the problems are so presented that children will wish to find the answers.

How can the teacher arrange classroom situations in which children eagerly accept Inquiry methods? One characteristic of the master teacher is that he is successful in devising challenging situations, statements, and questions; he seizes on spontaneously occurring situations at the opportune moment. Suitable problems for the elementary school must not be abstract. The resulting verbalizations are too frequently meaningless. To attempt to justify Copernican astronomy to a fourth-grade class as a more efficient conceptual scheme than Ptolemaic astronomy is almost as immoral as teaching Copernican astronomy as the only astronomy. To attempt to explain the rusting of iron, the burning of a candle, and the formation of oxyhemoglobin as exothermic processes to a fifth grade may be similarly unfortunate if the necessary conceptual structures and perceptual experiences are absent.

Concrete-empirical experiences, in the Piagetian sense, are essential for all children and particularly for younger children. The phrase "concrete-empirical" is not necessarily restricted to direct firsthand experience, but includes such vicarious experiences as photographs, films, filmstrips and personal knowledge. The postulation of a vacuum, so sensible and meaningful a concept to adults today, is perilously difficult to grasp, as its slow and hotly disputed rise in the history of science testifies. Yet, unless there is an understanding of what a vacuum is, how can one explain those phenomena which operate because of a vacuum? How can the lift of airplane wings, the card and water glass experience, the vacuum cleaner, the siphon, and the whole host of vacuum-related phenomena which are part of the world of the elementary school child be explained? To explain to a child that an egg is forced into a bottle because of the partial vacuum inside the bottle is to present him with a semantic puzzle if all that he knows of a vacuum is its verbal connection with vacuum bottle and vacuum cleaner. It is only when children have experience with a variety of phenomena, when they feel for themselves the force required to pull a rubber "plumber's helper" from a wall, and when they see the height of a column of mercury sustained by "something," that the existence of a vacuum begins to make sense.

Therefore, a prerequisite for the successful introduction of Inquiry in elementary schools is a carefully planned series of concrete-empirical experiences presented not as verification or as facts to be learned, but as "Something happens; how can we discover what makes it happen?"

Facilitating Inquiry

What else is required? Surely success must be based on a more permissive atmosphere than that which commonly pervades the traditional classroom. The essence of Inquiry is freedom, freedom to pursue lines of thought unfettered by textbooks or by the necessity of learning certain facts, concepts, and principles for their own sake. A permissive atmosphere is not willed into existence, nor are children the better for it if it emerges suddenly. Children will accept it if they have come from classrooms in which this notion of freedom was already accepted because of the teacher's orientation and because of the activities in which both the teacher and children were interested. But teachers and children who are accustomed to more autocratic and traditional ways of teaching and learning will best achieve freedom to investigate by taking it in relatively small doses at first. From a pragmatic point of view, the problems selected should be those which are likely to be successfully unraveled—that is, those in which children will be able to find out what happened and why it happened with little difficulty. From a psychological standpoint, frequent success is essential, and in the elementary school years, it is unnecessary to introduce purposefully the element of failure in the scientific enterprise. Indeed, many problems which seem to be appropriate for youngsters will end in unplanned and unexpected failures. This is one reason for the great potential of the new elementary-science programs described in Chapter 6. Most of their Inquiry activities have received a thorough classroom testing and are much more likely to be successful.

Some Characteristics of the Non-Authoritarian Science Classroom[2]

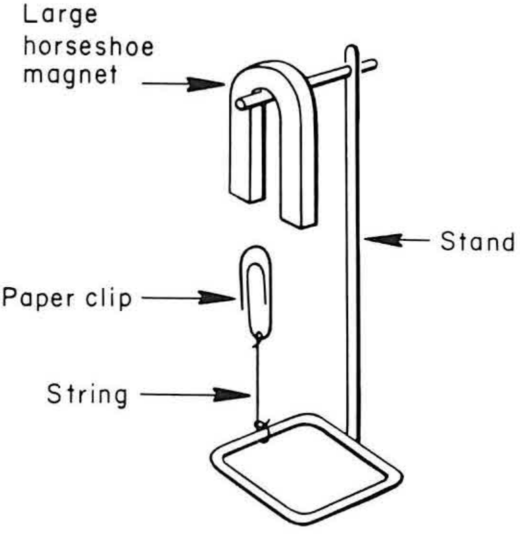
1. The questions and problems which are the subject of study often originate in the class, either from earlier work or as a result of a chance occurrence.
2. Procedures originate in child-teacher discussion, and questions and problems are cooperatively analyzed.
3. Children frequently propose hypotheses which lead to experimentation, observation, and further logical analysis.
4. Children use texts and trade books as sources of information and later verification; these sources provide additional data, not authoritative answers.
5. The teacher conceives of her role as that of guide, counselor, and consultant, not as "law-giver."
6. The data gathered from the various sources—experimentation, demonstration, reading, audiovisual aids, and personal experience—are cooperatively evaluated in order to assess a hypothesis.
7. Children evaluate their success (or lack of success) in solving the problem with which they were concerned.
8. The teacher never hesitates to use more traditional procedures when they are better for her purposes; for example, it may be

necessary for her to explain a particular phenomenon, either because information is unavailable, or because she can explain it more effectively.

9. Time is set aside for important activities. This time is available because there is no need to finish the textbook; there is no compulsion to complete a given number of units.

Motivating Inquiry

Setting the stage for Inquiry investigation with younger children is comparatively easy. Their curiosity about phenomena which are capable of stretching their frame of reference is frequently sufficient to begin an investigation if the phenomenon is exhibited (with or without teacher comment). For example, children who discover this piece of apparatus as they enter the classroom will raise a host of questions.



"What keeps the paper clip up?" "Will it fall if we poke it?" "Will it fall if the magnet is moved?" "How long will it stay up?" "What's between the clips and the magnet?" "Will a bar magnet work?"

The list of related concepts in this particular demonstration is startling: magnetic field, magnetic induction, forces in equilibrium, magnetic forces, gravitational forces, interactions, and the inverse square law. These concepts do not, of course, exhaust the list. There are problems sufficient for months of study should the class be so inclined.

The problem of motivating investigation is more difficult with older children, and yet, paradoxically, it is simpler. Activities must be chosen more carefully because many rather obvious centers of investigation ramify quickly—that is, they demand knowledge and data which are too complex or too abstract for fifth or sixth graders. Problems in chemistry, for example, are frequently of this kind. A chemical process as familiar as the rusting of iron is too complex unless it is handled at a superficial, observational level. On the other hand, it is not necessary to depend as much on concrete-empirical materials for initiating problems or for gathering data as is the case with younger children. Formal, propositional thinking is more readily available, along with greater maturity and informational understanding. Therefore, analysis of data at higher and higher inductive and deductive levels is possible.

An "innocent" question may lead to sustained interest and scientific endeavor by primary- and intermediate-level children. "Are all clouds the same?" "How do earthworms burrow into the ground? Do they go 'head' or 'tail' first?" "Do seeds grow if they are planted upside down?" "Do rocks look the same inside as outside?"

Introducing the problem

Ideally, problems are generated by the spontaneous interaction of children with the natural phenomena of their environment. In actual practice, however, the teacher must introduce many challenging and worthwhile areas of study to his class because the child's world is so narrow. The teacher must set the stage in such a fashion that his children literally besiege him with questions in their eagerness to learn.

Some teachers have discovered that a simple device such as this will stimulate a surprising interest in the study of rocks and minerals: Letter these words conspicuously on a large slab of stone (a flagstone): "I am a rock. I am made up of minerals. Are there other rocks and minerals in this room? What is the oldest rock in the room?" To introduce buoyancy, they prepare a Cartesian diver labeled as follows: "Push down on my rubber top. What do I do? Do you know why?" The enterprising teacher often relies on a science corner as a focal point from which new questions and the answers to previous questions originate. No science corner is complete without a "curiosity box," an interest-arousing container whose contents should be frequently changed. During one week, it may contain plant seeds, and its label may ask, "How many kinds of seeds do I have? Are they all the same? In how many ways are they the same? Different? Are my seeds alike on the inside?" The next week, it may hold a variety of leaves and be labeled with pertinent questions. The possibilities for stimulating desirable interests are endless. But it is not necessary to depend on the science corner for the initiation of classroom science activities. The appeal of the science corner for informal investigation by children is one of its most rewarding features. It is here that the salamanders, the aquarium, and the growing plants are maintained by volunteers.

One of the most effective methods of introducing a problem is by a demonstration which, although simple, is striking and challenging. The more startling the outcome, the more the child's normal response pattern is shaken, and the greater is his drive to search for a solution without falling back on the secure clichés of daily explanation. There is no more provocative way to introduce children (and adults) to an investigation of static electricity than by rubbing a hard rubber comb on wool or fur (may other materials be used?), and placing the comb in close proximity to a thin stream of water. As the water curves dramatically toward the comb, the children will literally explode with questions. It almost seems as if the stream of water is perversely denying the law of gravity and is endowed with a strange power of its own.

What approach is more promising than being surprised at the beginning of the school day in the act of preparing jars for studying insect responses to light? To the question, "What are you doing?" the teacher may reply, "I'm trying a little experiment. Would you like to help?" Is there a child who can refuse such an invitation? The resourceful teacher will find many opportunities to interest his children in activities which strengthen their ability to think independently and critically. On the other hand, not every task in science is necessarily productive in the sense described above. There *are* routine chores—feeding animals, cleaning the aquarium, and washing the glassware—which are necessary in efficient classroom management of Inquiry. And there are many desirable learning activities which are not necessarily centered on scientific thinking. But as a more or less arbitrary rule of thumb, whenever learning activities may be initiated by means of a provocative situation, better learning is likely to result, because of strong initial interest.

Science need not always be introduced in this fashion. It is not *necessary* to startle children into a learning situation, to fascinate, awe, and intrigue them, although there are some positive (as well as negative) values in this procedure. Indeed, the mere opportunity to handle concrete materials, to do things for themselves, to "play" is sufficient incentive for many children to carry on teacher-structured activities which are begun without a dramatic introduction. There are scientific domains in which spectacular demonstrations or provocative experiments are not feasible in the elementary classroom, and fascinating phenomena which are too difficult to investigate. For instance, it is rarely possible for elementary school children to understand the meaning of chemical reactions, and therefore the study of chemical reactions is best left to eighth- or ninth-grade children, as is the study of nuclear reactions and radioactivity.

Narrowing the problem

Once interest is aroused, the problem must be identified and incisively analyzed. The analysis of the confusing mass of questions, half-questions, vague statements, and unsupported assumptions of a group of youngsters inexperienced in Inquiry is a necessary although not a sufficient condition for success. Scientists agree that formulation of their problems is one of their most difficult tasks, and that all too often their path is more arduous because they have failed to ask themselves the "right" questions. Therefore, children will need much help in learning to formulate questions which are answerable; which, in other words, offer a reasonable promise of success with the materials available to the class. The question "Why do some things float?" is an invitation to disaster if addressed to second graders. It is too inclusive, too complex, and too general to be of directive value to them. The understanding that it assumes of causal relationships and physical phenomena is apt to be unjustified. A more effective restatement of the problem is the following: "How can we find out what things float? What things sink?" Or even more specifically, "Will this wooden boat float or sink? Will this piece of iron float or sink?" Children (and adults) rarely phrase such limited questions spontaneously, and therefore the teacher and class should cooperatively analyze the reasons for preferring the second questions to the first. They are not only more specific, but they are presented in the context of a particular empirical-concrete circumstance, which directs observation and experimentation.

The question as restated by the class may remain nebulous, or perhaps may be compressed into the straitjacket of overspecificity, so that causal understanding fails to emerge. For example, the question of what kinds of things float, if that is the primary question, is too limited for a group of fifth graders, who are prepared for a higher level of abstraction. On the other hand, younger children will immediately propose such answers as wood floats, boats float, tin sinks, which thus furnish a base for further investigation. After the operational phrasing of the problem and the proposal of possible hypotheses, the class must pool its knowledge in order to provide the necessary data. An alert child may add the complicating fact that boats made of steel are able to float and that submarines (made of steel) float or sink at will. With most children, these contradictory observations are perplexing. Few young children can distinguish the relevant from the irrelevant variables which complicate the analysis of floating bodies. Therefore, if no child makes the suggestion, the teacher must suggest that the physical composition of the floating object is not necessarily the best way of separating floating from non-floating materials. Children may mention shape as another characteristic of floating bodies. Should this concept fail to emerge, additional play with floating and non-floating objects should provide the necessary perceptual experience. Eventually, the proper hypothesis will be proposed. Children must now test their hypothesis on as many different materials, shapes, and liquids as possible. However, before they can conceive of floating on a high level of abstraction, specific concepts of density, specific gravity, weight, volume, displacement, equilibrium, and force must emerge. Younger children have not formed clearly defined, unequivocal weight and volume concepts; a large part of class time must necessarily be devoted to elucidating these concepts. Not until children are able to manipulate these ideas with some skill will they be able to understand *why* a submarine sinks when its tanks are filled with water, and *why* it floats when these tanks are emptied. It *is* possible for third graders to comprehend on a relatively abstract level the meaning of density and volume, and, indeed, to propose a reasonably adequate explanation of floating, but this meaning will not arise from a verbal-abstract teacher explanation or from rote memorization of the textbook. It will come from *many* firsthand experiences with floating and non-floating objects, experiences directed at eventual elucidation of these conceptual relationships.

Proposing hypotheses

If a problem is properly defined, that is, operationally limited, children will suggest intelligent hypotheses. They may not be correct, but, with continuing experience, their hypotheses will at least not be absurd. Although their hypotheses may not be testable in the classroom, this does not necessarily terminate the investigation. Children who are unpracticed in thinking up hypotheses and in assessing the validity of hypotheses of others will need direct guidance and kindly but critical assessment directed at improving their probes. It is well known that young children must learn (or be taught) to distinguish fact from fancy, the possible from the impossible, the natural cause from the animistic and teleological cause. Sympathetic discussion and critical evaluation of their hypotheses (and other statements) by both teacher and children is not possible in a period of ten or fifteen minutes once or twice a month. Time, in unrationed doses, is a requisite.

Older children (as well as many adults) often give unrealistic explanations when confronted with puzzling situations, particularly if they are unable to bring their own accumulated knowledge to bear. With practice and maturation, children reduce the number of non-natural explanations. Yet many responsible adults continue to believe that flowers are colored so that bees may be attracted, or that evolution occurs so that more viable forms of life may originate.

Hypotheses should be relevant; but the obstinate question "relevant to what?" intrudes itself. They should, of course, be naturalistic, couched in terms which lead to testing and verification. They should be simply expressed, embodying the fewest possible variable factors. Children can propose relevant hypotheses, but we remind you that time, practice, broad experience with many phenomena, and the existence of a somewhat rare intuitive power are factors which catalyze hypothesis formation.

The teacher who attemps to coax hypotheses from her class when both are inexperienced in Inquiry is apt to become discouraged very quickly. The conscious formulation of reasonable hypotheses is a difficult task for adults; indeed, it is the mark of the great scientist that he is able to derive testable hypotheses. Therefore, the first attempts by the novice at Inquiry should be with very simple observational or experimental problems, which are well within the grasp of her class. Even then, the pace will surely be too rapid for many children, and the rate of the entire group is quite likely to be unexpectedly slow—slow, that is, when contrasted with the traditional methodology of the recitation.

The teacher must continually encourage her class to test each of the hypotheses with questions such as these: "Is it reasonable? Does anyone in the class know of any facts which confirm or deny its validity? How can we find out? What experiments are suitable? Does the textbook have anything to say which will help us test the hypothesis? Are other helpful materials available in the library? At home?"

Most of the time, in a problem which is generated by the children or structured by the teacher (unless it is purposely delimited), answers will not come from page turning in the textbook because textbooks are not written to supply information about an infinite number of investigative concerns. They are, after all, textbooks, not compendia. Should the problem be a relatively simple, observational question—"Are all kinds of clouds the same?" or "Do all the leaves on a tree have the same shape?" or "What will happen if I drop a crumpled piece of paper and an uncrumpled piece of paper at the same time?"—the alternatives are few, and suggestions for testing these hypotheses will soon be forthcoming. But for a well-defined question such as "Why does a pencil in a glass of water appear to be bent?" or "What makes the rainbow?" the hypotheses are potentially unlimited and at a high level of conceptual complexity. Unless children possess a rich background of experience with the pertinent facts and principles, it is unlikely that fruitful hypotheses will be proposed by fourth or fifth graders. Strategically it is probably much better to approach these problems after children have handled lenses and have learned that light is refracted in passing from one medium into another of a different refractive index.

Suitable problems for younger children require little cognate conceptual data prior to their formulation, and can be directly solved with experimental or observational data. With older children, the question "Why does a pencil in a glass of water appear to be bent?" may evoke, in addition to the "I don't know's," the statement that "the water does something to the pencil." A more delimited hypothesis is rarely produced except by those who already know about the refraction of light. The teacher must once again set the stage for evoking the desired hypotheses, after discussing the shortcomings of the hypotheses that are advanced by the class. Does the class believe that the pencil is actually bent? He may suggest varying the conditions of the demonstration to see whether or not the bending still occurs. Will the pencil be bent as much if it is observed from a different angle? The children should examine the pencil from many angles. The pencil may be immersed completely. Does this make a difference? Does the pencil bend in other liquids—rubbing alcohol, glycerine, salad oil? By this time, a number of observations concerning the angle of view and the media will emerge. The statement that the pencil is bent because of the refraction of light will probably never be made spontaneously—it will, however, come from the cooperative discussion between teacher and class, as they assess their data and attempt to find a simple, natural explanation.

With practice over a lengthy period of time, children improve markedly in their ability to formulate and evaluate hypotheses, but this practice must be with concrete, directly apprehendable problems which are affected by a relatively small number of variables. Were the kindergarten to twelfth-grade curriculum predicated on an Inquiry methodology instead of scientific concepts and principles, there would be ample opportunity for children to apply continuously, from month to month and from grade to grade, the skills and habits of learning to learn science. The pressures which exist in any comprehensive curriculum for completing the syllabus must inevitably lose their terrors when there is no longer the compulsion to "cover" air, water, health, electricity, growing things, and prehistoric animals during the nine teaching months.

Older children fall back on authority in proposing and testing hypotheses more frequently than do younger children, perhaps because of their indoctrination in authoritarian procedures. Younger children must rely more on direct perceptual knowledge and guessing, although experimentation is frequently attempted by children of all ages.

Rather limited research in elementary schools indicates that children in permissive classrooms in which discovery procedures are practiced are less dependent on authority for proposing and testing hypotheses than are children in non-permissive rooms. It is possible that their hypotheses, although more numerous and ingenious, are not necessarily more accurate. They are, however, better able to suggest tests for their hypotheses by experimentation and observation. There seems to be no positive correlation between intelligence and ability to test hypotheses empirically; indeed, measures of intelligence may be unrelated to the abilities required for critical thinking.[3]

Analyzing assumptions

As the relevant information is proposed and evaluated, there is a concomitant opportunity to identify and assess the assumptions, implicit and explicit, on which answers depend. Statements such as these will be made: "Light things don't push aside as much water as heavy things do," "Heavy things sink," and "Things can float only on water." Such statements are obviously based on partially or completely erroneous assumptions. However, elementary school children are not uniquely unskilled in analyzing the assumptions which they bring to problem solving. Analysis of assumptions is not ordinarily part of the daily thought processes of either adults or children. The hidden assumptions in the tumbler-water-card demonstration described at the beginning of this chapter have been analyzed. Almost every scientific experiment or demonstration rests on a number of assumptions which must be clarified (or at least recognized) if the experiment is to have any meaning.

The teacher must continually assist children to recognize and resolve the assumptions which underlie Inquiry procedures. Terms must be carefully defined, pertinent variables selected, and problems of measurement, control, and technique carefully examined. There is no shortage of source material to promote skill in analysis of assumptions. For example, a popular text for teachers suggests that in order to answer the question "Can mushrooms and other fungi make their own food?" children remove some mushrooms or bracket fungi from their habitat and, after placing them in water, compare the viability of these fungi with that of the fungi in their original locations. The conclusion given is that the fungi die because, without chlorophyll, they are unable to manufacture food. There are a number of questionable assumptions in this experience, however. For example, it is possible that the fungi were so severely damaged by their forcible removal that death was inevitable.

There is also the traditional demonstration that air exists in apparently solid materials. If a lump of soil is immersed in water, bubbles of "air" are soon trapped in the container. These bubbles are usually said to come from the soil, and therefore soil must contain trapped air. But, this conclusion is not certain. For example, has the gas been tested and conclusively identified as air? If indeed it is air, may it not have arisen from a reaction of the organic acids and other materials of the soil with water? Perhaps it is the air dissolved in water which escapes as the water warms up? It is evident that many unwarranted assumptions may be implicitly accepted, resulting in an answer of dubious worth.

Questioning assumptions is also important when additional data are required. Questions which, on the surface, are rather simple—"What makes the sky blue?" "Why are there so many earthworms on the ground after a rainstorm?" "How long can a fly fly without stopping?"—are in reality exceedingly complex. The simple demonstration at the beginning of this chapter was anything but simple, because of its many implicit assumptions. Obviously, many problems will call for ingenuity in formulating hypotheses, a prolonged search for data from a wide variety of sources, and a sympathetic yet demanding teacher as a guide, if satisfactory answers are to be formulated. For this reason, the tested Inquiry experiences in the new elementary-science programs will be of great value in science teaching.

Controlling experiments

The most common and at the same time the most flagrant violation of the elements of scientific experimentation is the uncontrolled manipulation of variables. Controls must always be used. If the class is studying the growth of plants and the germination of seeds, for example, one of the questions inevitably posed, either by teacher or children, is "Will seeds begin to grow in dry soil?" Thus, to answer this question, a number of pots of dried soil, each planted with some quick-germinating seeds such as radish seeds (each pot is exactly alike as possible), must be placed in the same environment. After a few weeks, half the pots are watered and kept moist, although not saturated. The growth which results in the watered pots will be sufficient to result in the more or less valid generalization that radish seeds apparently do not germinate in dried soil in the time period, but will germinate in moist soil. All conditions are the same (within the limits practicable in the classroom) with the exception of moisture, and the limited generalization is valid, whereas if dry soil alone had been used, the lack of growth could be ascribed to defective seeds.

Ingenuity is frequently necessary in planning suitable controls, and adequate controls are often impossible to maintain in the classroom. Observations of many phenomena call for little or no experimentation, but eventually, despite the obvious influence of certain variables, final confirmation must be left to controlled experiments. Suppose that in examining an ant trail, a pathway from an ant nest to a source of food, the pathway is rubbed over by one's fingers. Some ants may become confused and lose the trail. If this occurs, is it because the trail was erased, or because a human odor was added? Is there any simple way to tell? Can you propose a controlled experiment which will lead to a valid conclusion?

Whatever the data, they must not be overgeneralized! Conclusions must be limited to the data, unless it is known with great certainty that the specimens or samples, as well as the conditions, are typical; that is, that they are random specimens selected from a general population. Could one legitimately conclude from the card-and-inverted-glass demonstration that all glasses, all cards, and all liquids behave in the same way? Of course not; no more than we could say that all seeds fail to germinate in dried soil. It is an overgeneralization to say that children will always overgeneralize. But they often do, and the wise teacher is always careful to limit the conclusions of the class to their legitimate and appropriate realm.

Planning and evaluating Inquiry teaching

The teacher should frequently ask himself questions such as these in planning and evaluating the potentialities of Inquiry experiences:

1. Is it possible for my children to formulate the problem in operational terms?
2. Does the problem lend itself to a thorough but simple analysis which is not excessively superficial?
3. Do my children know enough science that, using various sources of information, they will be able to propose intelligent hypotheses?
4. Are there enough firsthand experiences to sustain interest, to develop skills, and to provide the necessary direct contact with reality from which concepts grow?
5. Are classroom (and home) facilities adequate for gathering data and for testing hypotheses?
6. What scientific concepts and principles are included? Can they be fitted into a coherent structure?
7. Do the experiences lend themselves to critical analysis; to the evaluation of hidden and half-hidden assumptions; to the growth of skills that are essential to success in scientific thinking?
8. Is enough time available for exploration in depth?
9. What is the relationship of these activities to the great ideas of the sciences? (See Chapter 5.)

Some examples of Inquiry

Let us now examine a teacher-initiated problem more closely to illustrate and to summarize the points previously made. Assume that a fifth-grade teacher has set up a simple pendulum, constructed of a length of string and a lead sinker so supported that the pendulum swings freely. This may be a single demonstration, unrelated to previous learning, to serve as a motivational instrument, or it may be one component of a series of activities on gravitational force. If the teacher asks a child to pull the sinker to one side and then asks the class, "What will happen when Susie lets the sinker go?" several answers will be heard. The most probable is that the sinker will swing back and forth. The teacher may enlarge on the question by asking how long the pendulum will continue to swing and how high it will swing at each end. After the pendulum has swung several times (how many are desirable?), he may ask how the rate of swinging can be changed. How can the speed of the pendulum be measured? Children will suggest different weights, string materials, string lengths, and arcs. The discussion may center on this question: "What are the variables which change the time of swing of this pendulum?" Subsidiary problems of length, arc, and weight (someone invariably suggests pushing the sinker) are quickly proposed. Children propose hypotheses for each sub-problem: "Making the string longer makes the pendulum swing more slowly." The teacher and class must be alert to the need for keeping all factors constant save the experimental factor. The teacher must then lead the class to propose controlled experiments to test their predictions. The data gathered by the class should be entered on a data sheet designed for the purpose. Small groups may carry out these experiments and then report to the class.

The assumptions which underlie the experiments must be extracted and analyzed. Does it make any difference where the weights are tied on the pendulum string? Does the air affect the pendulum? Do the vibrations of the pendulum stand affect the period of the pendulum? What about deviations from the plane of the swing? Does changing the location of the pendulum affect the results? What other assumptions about the conditions of the experiment may be proposed?

The data should be adequate for a decision on the alternatives. Either the children's hypotheses are right, they are wrong, or the data are not yet of a quality which permits decision. If the hypotheses are right, that is, if they appear to be valid, it should be possible for the children to make a two-branched prediction. First, what will happen if each variable is altered in turn? Second, how can this knowledge be utilized to make other predictions? That is, what general predictive power comes from knowing the effect of varying the pendulum variables? As an example of the first kind of prediction, the teacher may ask, "What should the length of the pendulum be for a one-second (or two-second) pendulum period? If the period (the dependent variable) and the length (the independent variable) are plotted graphically, it is a simple matter to find the pendulum length for a period of one second. Graphical analysis is particularly valuable because it bypasses the formal mathematical treatment of high school and college physics. The questions "Can we make a pendulum with a baseball bat?" and "How can we speed up or slow down a pendulum clock?" are examples of the second kind of prediction.

The teacher must continually point out the necessity for identifying pertinent conditions, significant objects, and relevant procedures. He guides the class in assessing the value of the suggestions and questions that are proposed and in ascertaining those variables which are essential. It is particularly imperative that he help children identify those factors which change or can change and thereby affect the results. Few children have had the opportunity or the desire to vary experimental conditions systematically in order to learn what may happen. If they do tinker with the variables, they are apt to do so unsystematically, changing two or more simultaneously. (See pp. 45–55, Chapter 2.) If children alter both the length of the pendulum and the arc through which the pendulum swings, anomalous results are obtained. To cite another example, in the experiment with the "bent pencil," a simultaneous variation of the liquid used and the angle of viewing will give meaningless results.

The work of Suchman at the University of Illinois is an excellent verification of the belief that children can propose and test hypotheses. (See pp. 57–60, Chapter 2.) They can learn to phrase their questions more narrowly so that specific answers may emerge. There is no dearth of opportunity for training in good habits of logical thought if children are not restricted to dull memorization of the textbook or to a routine course of study. Let children predict the results of a particular action! Do *not* supply the answer in advance, nor allow children to turn to authority before their own analytical schemes are found wanting, or before additional verification is required. Continue to ask "Why? How do you know? How can we test this? Are you sure? How can we find out? What will happen if we do what you say? What do we need in order to do it? Where can we find out? What do we do next?" An interesting variation of this procedure is to quote some scientific fact, (e.g., pressure of water increases as the water depth increases), and then to ask the class to find some procedure by which this fact may be verified. A teaser demonstration, such as the card-and-inverted-glass demonstration described earlier, or the evolution of oxygen from *Elodea* when sunshine falls on the plant, is even better.

The teacher may also present a few facts, either verbally or experimentally, and then cooperatively draw from these facts the fullest possible set of inferences. For example, if the teacher rubs a hard rubber comb with wool and quickly touches the comb to a simple "Rice Krispies" electroscope, the two bits of cereal are attracted to the comb and then quickly fly apart. If the comb is then rubbed with a sheet of polyethylene film (a dry-cleaner's bag) and brought close to the electroscope, the bits are attracted to the comb, touch it, and then fly apart again. The comb repels the cereal kernels if brought near them, and they move closer to each other (although they do not touch) when the comb is taken away. What hypotheses about the behavior of the cereal kernels may be derived from these experimentally observed facts?

Summary

The Inquiry approach to the teaching of science is neither a panacea for the infirmities of contemporary science instruction nor an infallible guide by which the aims of science teaching will be attained. It is, however, the most promising direction for elementary school science, because it is a methodology which offers a unique opportunity for children to grow in mastery of both the processes and products of science. Inquiry *is* more difficult to plan, to sustain, and to evaluate than conventional, textbook-centered teaching, and educators are not convinced that Inquiry is feasible in most elementary schools, but its psychological and conceptual strengths are such that elementary education would be remiss indeed in not venturing boldly into a teacher-education program in science that is centered on Inquiry.

The essence of Inquiry is experimentation – genuine experimentation with many phenomena in order to answer questions without relying on the crutch of a textbook or other authority. (See Chapters 7 and 12 for examples of such experiments.) Concomitantly, there is required a permissive, cooperative atmosphere in the classroom, which encourages both children and teacher to examine the evidence they find, to assess their hypotheses and assumptions, and to come to the most reasonable and logical conclusions consistent with the evidence.

These requirements demand far more from both teacher and class than traditional science instruction, but the potential rewards are so attractive that it would be folly to delay training elementary school teachers in the habits and procedures of Inquiry. Little is to be lost by a shift to Inquiry – the past record of elementary-science teaching speaks for itself. It is equally unreasonable, however, to expect teachers who have been taught science as a rigid hierarchy of facts, laws, and principles to master Inquiry procedures overnight. The simple scientific experiences described in this chapter may serve to orient teachers to the kinds of doing and of thinking which will increase their probability of success in Inquiry teaching.

For further study

1. Select a scientific experiment from an elementary-science textbook and analyze its pertinence for Inquiry. To what extent is it psychologically and pedagogically functional? To what extent are its outcomes consonant with Bruner's postulates for discovery teaching (p. 140)?

2. How have conventional curricula attempted to solve the process-product dichotomy?

3. What are some of the important elements in successful Inquiry teaching?

4. "Ideally, problems are generated by the spontaneous interaction of children with the natural phenomena of their environment." Is this a feasible guide to practice in the classroom?

5. What are some of the important assumptions on which these experiments or events are based?

   (a) A metal expands when heated.
   (b) An inflated balloon shrinks when it is cooled.
   (c) The rate of chirping of crickets increases as the temperature increases.
   (d) An electric current decomposes water into hydrogen and oxygen.
   (e) The probable appearance of dinosaurs may be reconstructed from fossil remains.

6. Formulate some tentative hypotheses to explain these phenomena:

   (a) Water expands when it freezes.
   (b) The growth of animal or plant populations sooner or later levels off.
   (c) Silt and gravel carried by water may be deposited to form a delta.
   (d) The eye of a hurricane is relatively calm.
   (e) Dry cells which stand for long periods of time corrode.

7. To what kinds of scientific problems is graphical analysis applicable?

8. Describe in detail an experiment, taken from a children's science book, that is not valid because controls are omitted. Explain how controls may be incorporated to make the experiment valid.

9. How do you know that a conclusion is valid? How do you know if it has been overgeneralized?

References

1. Bruner, J., "The Act of Discovery," *Harvard Educational Review*, 31, Winter 1961, pp. 21–32.

2. Adapted from Atkin, J. Myron, "A Study of Formulating and Suggesting Tests for Hypotheses in Elementary School Science Learning Experiences," *Science Education*, 42: 414–422, December 1958.

3. *Ibid.*, pp. 414–422.

5

Foundations of the science curriculum

Goals of science education in the elementary school

The goals of science instruction in the elementary school are as numerous and as diverse as the committees of teachers which write the dozens of science curricula published each year. The reader is well aware that the authors of this book are chiefly concerned with one segment of these elementary school objectives—"cultivation of the inquiring mind." It is reasonable to think of the study of the sciences as one of the pathways to growth in heuristic thought. The sciences, of course, include many affective and philosophical concomitants which are a part of science instruction but are somewhat subordinate to the goal of "the inquiring mind." Science is one of the few disciplines whose wealth of phenomena is open to direct observation, to manipulation, and to the application of both intuitive and rigorous logic. These are operations which are invaluable in nurturing scientific thought.

In science teaching, the phrase "inquiring mind" refers to the predisposition to find out what makes things happen. The inquirer is critical, reluctant to accept an *a priori* explanation, whether authoritative or not, without applying to it the tests of experience, of experiment, and of reason. The inquiring child is not content with the answers of the textbook and of the teacher, nor is he ready to accept the world around him without question.

We believe that one of the functions of elementary science is to help children to recognize a hypothesis, its strengths and weaknesses, and its implicit and explicit assumptions. The teacher ought not be concerned with teaching the distance of the planet Mars from the Earth and the law that the strength of a magnetic field decreases inversely with the square of the distance from the magnet, but instead he should strive to teach how scientists know how far away Mars is and how they have learned that the inverse-square law applies to magnetic phenomena. Throughout their school years, children should grow in ability to recognize whether or not a statement is based on authority and whether an inference from data is justified. They should be able to decide that a particular relationship appears to be causative and to judge that the data have been completely exploited and properly interpreted.

These complex skills, traits, and abilities are essential parts (at some level of achievement) of the overall pattern called "the inquiring mind." In short, teachers may properly concentrate on fostering the intellectual processes which lead to better thinking, employing subject matter which is selected because of its relevance for inculcating these skills and habits.

One of the most frustrating of the many problems confronting science educators is the difficulty of formulating behavioral objectives. Only by specifying desired behavior patterns for children, as the American Association for the Advancement of Science elementary-science curriculum has done, is it possible to assess the degree to which objectives are attained. (Chapter 6 gives an analysis of this curriculum; Chapter 11 gives a rationale for defining and evaluating behavioral objectives.) Therefore, in teaching elementary science, the teacher must, at a very early point in his planning, describe the actual behavior changes he anticipates. For instance, the habit of relating cause and effect in physical happenings is assigned a high priority. The child has begun to master this habit if he *knows* that opening a switch causes a light to go out; that a tree shadow moves because the sun is moving through the sky; that the disappearance of a ship over the horizon is a result of the Earth's curvature. The child, however, does not simply master cause-and-effect explanation once and for all. The nature of the phenomena, the degree to which he brings a sound conceptual structure to new happenings, and his previous success in using such explanations are reason enough for postulating a series of levels of understanding of cause-and-effect relationships.

Of course, there are many other valid reasons for including science in the curriculum of the schools. Many of the facts and principles of the sciences affect modern life, from both a consumer's and a producer's standpoint. Concern for safety requires that children be scientifically literate about current electricity, combustion, kinetic energy of impact, and nutrition. It is a truism, however, that the average life may be lived in an average way without much comprehension of the interplay of scientific and technological knowledge in modern society (with the exception of health and safety). One need know very little science to start, drive, and park an automobile; to go shopping; or even to raise a family. The appeal to the utility of scientific knowledge in the learner's experience is a weak reed on which to lean, for the facts of science often change quickly, both in their actual "truth" and in their utilitarian importance. A child who learns how a motor operates may soon find that he is technologically obsolescent because invention confronts him with new types of motors whose mechanical arrangement is different.

Manipulative skill is probably not an important objective of itself, because few important manipulative skills emerge from elementary-science instruction. The ability to heat liquids in a test tube without scorching one's fingers is useful, but it is easily acquired and is too trivial to be worth striving for. For psychological reasons, however, manipulation has a vital role in Inquiry teaching.

There has long been a call for nurture of "the scientific attitude," which generally is held to encompass such habits (attitudes?) as lack of bias, objectivity, accuracy, suspended judgment, and avoidance of superstition. These attitudes, which are surely worth striving for, are probably best acquired within the scope of Inquiry. Related to this "scientific attitude" is the deeply reverential bow of the pertinent literature to what is termed "appreciation of science and scientists," which means recognition of the contributions of scientists (individually and collectively) to the evolution of science and to the incorporation of the results of scientific discovery into the economic fabric of society; the phrase may also be extended to include the place of science, with its characteristic set of criteria, procedures, tools, and disciplines, in the realm of the subject-matter disciplines.

Few of these reasons for teaching science in the elementary schools are trivial. Those goals which are least important are unfortunately the working goals, which, because they are easily assessed, are the practical outcomes in the schools—the learning of facts and generalizations as ends unto themselves, from books and from vicarious experiences. The focus of science education has been on the product component of the sciences. If a shift to the process component occurs, process must not be taught as a product. That is, process must not be given to children in a printed set of directions equivalent to "the scientific method," but instead discovered and explored anew by each generation of children.

Role of investigative activities

Precisely because the major goal is that of the inquiring mind, it is appropriate that we seek to achieve this goal by relevant, Inquiry-centered activities. Although the inquiring mind may emerge from a diet of educational passivity, it is probable that only an innately gifted child will break out of the prison walls of mental rigidity.

Albert Einstein, in an autobiographical note, comments on his frustrations with teaching rigidity:[1]

> I soon learned to scent out that which was able to lead to fundamentals and to turn aside from everything else, from the multitude of things which clutter up the mind and divert it from the essential. The hitch in this was, of course, the fact that one had to cram all this stuff into one's mind for the examinations, whether one liked it or not. This coercion had such a deterring effect [upon me] that, after I had passed the final examination, I found the consideration of any scientific problems distasteful to me for an entire year.

Children who are taught at, told at, questioned at, who have never enjoyed the opportunity of finding out for themselves, who never realize that there is (or ought to be) a social climate which accepts individual investigation, are unlikely to mature into the scientifically literate adults our society needs.

Therefore, we believe that much, perhaps half to three-quarters, of the total elementary-science experience should consist of investigative activities. These are not traditional laboratory experiments, of course. Depending on the problem, any valid procedure—whether observing, questioning, viewing, or reading—for inquiring into that which is not already known (unless verification is specifically desired) is appropriate. However, teachers *must* remember that unless children are given continual and sequential opportunities to use their senses, their minds, and their skills, they will inevitably be forced back to the convenient simplicity of traditional learning about science.

In a sense, laboratory experiences *are* the content of elementary science, and it is as a result of these experiences that pertinent behavioral changes occur. We have previously remarked that encyclopedic treatment of the facts, principles, and concepts of science is an impossible kind of elementary science. Curriculum makers *always* select content, although their criteria are dissimilar. It is self-evident that an infinity of facts and ideas exists. Which ones shall we choose, and why? We are critical of the cyclic or spiral curriculum organization as it presently exists, because its major goals are the inculcation and development of scientific principles. If habits of thinking, ways of analyzing problems, are the important goals, then it is important that these habits and skills be utilized in tasks which will strengthen them. Activities should be chosen because of their relevance to Inquiry, and not because of their potential for learning facts and concepts. According to this interpretation, the content of elementary science is its process—how scientists work, the kinds of criteria which direct this work, and the evolution of the scientific structure. Mastery of traditional content, although unobjectionable of itself, is not the most important reason for studying science.

The non-structured curriculum

The physical act of centering the curriculum on the process of science is no guarantee that the teaching act will be process-centered. The process-oriented curriculum may be completely outlined from grade to grade, as it is in the American Association for the Advancement of Science program, or, on the other hand, be quite informal, incidental, and unstructured. We believe that the professional teacher will be happiest with a relatively unstructured curriculum, which suggests rather than dictates. He alone knows the relative maturities, reading abilities, quantitative strengths and weaknesses, interests, and socio-economic status of his class, and therefore he is the best judge of the capacities of his children. With the proper guidance, he will select activities consonant with his goals, his class, and his teaching environment. The teacher who is unprepared for this challenge is unlikely to be successful in breathing life into even the most minutely planned curriculum.

The "curriculum" is the sum total of classroom activity. Courses of study, elaborated endlessly on countless sheets of paper, are not the curriculum. The school's philosophy, its physical facilities, the conditioning to Inquiry learning by both children and teachers, the teacher's own intellectual and personality resources—these are the real vitals of the "curriculum." Now, it may happen that a third-grade teacher is unaware of what the second- and fourth-grade teachers are up to, but it is possible only if she prefers ostrich-like isolation. Teachers in most schools are encouraged to know what their colleagues are teaching, what skills and habits of thinking they insist on. A course of study planned by and for an individual school makes more sense than a town-wide or state-wide course of study, because of the inevitable diversity and estrangement from the planning center. A comprehensive curriculum is most suitable as a resource from which teachers may extract conceptual assistance, experiment planning, and evaluative aids. Teachers who know both the prior educational achievements of their children and the demands which the future will make on these children will be ready for a program of science instruction which capitalizes on past strength and endeavors to overcome revealed weakness.

The third-grade teacher who knows that most of her children have already planned simple investigations of rainfall, of the flow of electric current, and of the balanced aquarium will be more confident (and more successful) in guiding new investigations. Research in the realm of cognitive structure assures us that any necessary skills and habits can be learned, but only if their inculcation is continually sought and watchfully practiced in activities planned for the purpose. In this sense, the curriculum must have a structure. Each school is responsible for selecting, on some order of priority, the skills, habits, and attitudes it wishes to develop, and for planning the total framework (and many of the experiences) for this purpose.

Assuming that this idea is valid, there is no reason for "covering" all areas of scientific knowledge. The rationale for the traditional kind of curriculum arises from the belief that children should have some understanding of their environment and therefore ought to be introduced to concepts (perhaps entire fields of science) of which they have neither knowledge nor interest. This philosophy carries with it a necessary superficiality, because it presupposes a need to "cover" the textbook. It is surely desirable for children to learn as much as they can about everything which is known, but because of the hydra-like growth of knowledge, selection is imperative; it is best to allocate to any one grade a small number of scientific phenomena, to be explored through time-consuming investigation. Here too, intra-school planning will insure that the children have been exposed to concepts from each of the many fields of science by the time they leave the school. This is a sub-species of the "block-and-gap" approach which has long been advocated for high school and college instruction by some critics of modern education. The "blocks" consist of drastically limited portions of knowledge, such as genetics and respiration; the corresponding gaps may be the omission of the systematic survey of the animal kingdom which has traditionally been the major content of biological education. The block is treated in depth, and its implications are rather fully explored, on the assumption that what is learned well is more significant than an epidermal exposure to a vast body of facts. The philosophy of the "block-and-gap" approach is well summarized in Rogers' words:[2]

> "This is *your* class," I would like to say to my colleague. "Make your own choice of topics and do not try to copy mine. Be careful not to choose too many, and to make a selection which will show interconnections, making some kind of framework of science. Then you and your class can go ahead

> and think and argue and discuss and learn about science. At the same time, the class will learn some scientific material. Though you choose only a few topics, and though much of your attention and theirs is concentrated on methods and ideas, they will learn some facts and learn them well enough to seem well educated in science in the old-fashioned sense. And they will be happy to continue reading and learning for the rest of their lives."

If this is a valid point of view, then teachers should choose the proper "blocks"; that is, those curricular segments which offer the maximum promise for goal achievement.

The themes and schemes of science

There are some guidelines for selection of "blocks." One of the most fruitful, because of its relevance to science as process, is to choose those activities which lead directly to the framework of *conceptual schemes* (the principles, laws, and theories) and their associated integrating *themes. Themes are relatively few in number. They are the ideas which are demonstrably powerful in explaining many different kinds of phenomena.* They are generally high-order abstractions, almost axiomatically accepted because of the literal impossibility of proving their "truth" mathematically or logically. The energy relationships of matter and the concept of atomic discontinuity are typical themes.

A conceptual scheme, to repeat Conant's words, is "*a working hypothesis on a grand scale.*" The cell theory, the atomic theory, and the Ptolemaic solar system are examples of conceptual schemes. In every conceptual scheme, constructs such as energy, force, motion, time, space, and interaction are markers which guide man in exploring the scheme. Therefore, we may think of the framework of science instruction as a network of horizontal and vertical members—the great themes are the integrating elements, the vertical beams; the conceptual schemes, the horizontal beams, are the theories, hypotheses, and principles of the sciences. The matrix in which these structural components are embedded is, figuratively, the process elements of science.

The reader may look at themes and schemes in yet another way. Schemes may be thought of as the major ideas of the individual scientific disciplines (philosophically this point is not strictly valid), whereas themes are the ideas which tie the individual disciplines together and give them their relational strength. The disciplines themselves are integrated because of the power of the themes to clarify many complex problems which cannot be solved by the concepts of *one* narrow specialty. For example, in order to unravel the tangled threads of photosynthesis, a combined attack by biologists, biochemists, biophysicists, mathematicians, and statisticians is necessary. The very existence of the compound disciplines of biochemistry and biophysics is evidence of the value of a unified attack on the new (yet so often ancient) problems of the sciences.

The inherent complexity of science is like the perplexities which face us today in the education of children. The best talents of teachers, educational researchers, psychologists, sociologists, and neurologists are just beginning to provide reasonable theories of how children learn and how we can capitalize on learning theory in teaching them. Complete integration of the sciences, although theoretically desirable, is impractical in the schools, because children are not intellectually ready to grapple with complex problems. As a result, suitable problems for investigation are probably best selected from individual scientific disciplines, one at a time. This should not be taken to mean, for example, that living things are to be studied only in a biological setting, but rather that satisfactory progress can be achieved without extraordinary multi-disciplinary knowledge.

The child's conceptual framework can assimilate new phenomena and incorporate them into new and higher schemes. The availability of these schemes in his cognitive structure provides a pattern for understanding new phenomena. In turn, this framework will be incorporated into a new and more highly organized frame of reference. The availability of these structures provides for the child a pattern for understanding the phenomena which he encounters and for assimilating new ideas with greater ease and economy of time and effort. As an example of the power of a conceptual scheme, the hypothesis that life processes are similar in all animals provides a great deal of information about common animals; it also facilitates making inferences about other animal forms by extending knowledge from known forms. The knowledge that oxygen is necessary for respiration in frogs and men leads to the justifiable inference that it is necessary for salamanders and rabbits. It provides a key to understanding why an earthworm, immersed in water, will continue to survive for some time; it also leads to an investigation of the reasons for the inability of the higher animals to survive under the same conditions. Viewed in this way, the scheme is fruitful—it not only "explains" certain observable phenomena, but it leads to new queries, new clues, and new predictions. Children who have mastered this scheme should be able to predict that fish must have some way of obtaining oxygen in water, and that man, because he has no way of doing so, must perish.

This is a rather trivial example of the inherent power of the scheme, but it is nonetheless illustrative. (See Chapter 1, pp. 2–3 and 30–31, for other examples.) The child who has begun to incorporate into his thought patterns the first levels of understanding of these conceptual schemes is well on his way to scientific literacy, because he has become aware of the grand conceptions which give structure to both the sciences and his own thought process.

All the schemes of the sciences are not equally well-defined. The physical sciences of astronomy, physics, and chemistry, the most quantitative and the least "complicated" disciplines, are the most completely schematized. The principles of the biological sciences are more difficult to formulate and to apply because of the great variation between individuals of the same species, the almost infinite number of variables, and the formidable obstacles to rigorous experimentation. The earth sciences are faced with similar limitations, although such statements as "The earth's surface is continuously changing" or "Past changes in the earth's structure were caused by the same forces which are operating today" are undeniably predictive and suggestive.

The use of Inquiry teaching for enhancing scientific thinking does not conflict with the study of the structure of the sciences, as described in the preceding paragraph. These are not mutually exclusive propositions. In accord with our philosophy, we believe that the most important outcome of science in the elementary school is the growth of ability to think critically and constructively about science; but note that this thinking is science-centered, rising out of the content of the sciences and strengthened by periodic application to the sciences.

Because both conceptual schemes and fundamental themes are of such pertinence and strength in clarifying science for the layman, it must follow that teaching which attempts to portray science as a synthesis of what we know and how we know it must be organized around these schemes and themes. Therefore, the activities chosen should be those which will contribute to their assimilation into the cognitive patterns of the child. Thinking is rooted in that which is thought about. In science, that can only be the relationships which the individual sciences exhibit, internally and with each other. In pursuit of this ideal, children will learn a great deal of science even though noticeable gaps in their education (at least on paper) will exist. They will be challenged to an exciting, cumulative school life. Children will learn many facts, but, more important, they will know why these facts are important, how they are derived, how their reliability is assessed, and why, in the course of time, facts change. They will know that the concepts and principles of the sciences are not immutable but, because they are manmade, change in response to societal change. In essence, what we are describing is a strategy for achieving a kind of learning which, hopefully, will result in a kind of intellectual growth which is now discouraged by the sterility of the conventional classroom monologue.

There is no consensus on the specific conceptual schemes or themes which will be most fruitful in modern science teaching. The suggestions which follow are surely not divinely inspired. They are promising, but they are not unique; other equally reasonable propositions are conceivable. At the very least, they are sufficiently comprehensive to permit (perhaps even to require) the style of investigation proposed.

The themes

One of the most useful lists of ideas comprising the structure of science is that proposed by a special committee of the National Science Teachers Association.[3] Their themes are comprehensive and fundamental because they interact with every phase of contemporary science. The themes are not proposed as absolutes, valid everywhere and forever. They are, however, the best assumptions we have today to explain the wide variety of schemes which make up the sciences:

1. All matter is composed of elementary particles which may, under certain conditions, be converted into energy; energy may, also under certain conditions, be transformed into matter.
2. The particles of matter interact with each other.
3. Because matter exists in time and space, and because the particles of matter interact, changes must occur in time and space.
4. Matter exists in a variety of forms, arbitrarily classified by their complexity.
5. The distribution and behavior of matter in the universe is often best studied statistically.
6. The interactions of matter tend toward equilibria in which available energy is least and random distribution of energy is greatest; total matter-energy in a closed system is constant.
7. Motion of the particles of matter is one of the major forms of energy.
8. The processes of the past are those of the present and the future.

1. *All matter is composed of elementary particles which may, under certain conditions, be converted into energy; energy may, also under certain conditions, be transformed into matter.* The belief that matter is composed of simpler particles is of ancient origin, having been proposed as early as the fifth century B.C. by such Greek philosophers as Democritus, Empedocles, and Anaxagoras. Theirs was not a scientific theory, because they did not give atoms chemical properties; nor were their arguments such as to permit fruitful prediction about combination of atoms; nor could they explain chemical phenomena in a naturalistic, consistent way. Their atomic speculation was untested by experiment. Not until the great chemist John Dalton proposed his atomic theory in 1808 was there a

scientific basis to the belief in the elemental nature of matter. Dalton assigned certain specific properties to each kind of atom. He asserted (on somewhat dubious evidence) that different kinds of atoms exist; that they interact; that the atoms of each particular element are identical, and that the properties of these elements change when they are combined. Dalton explained Proust's law of definite composition by the hypothesis that atoms are unchangeable and that when different atoms combine, their compounds must be of a fixed composition.

The cogency of Dalton's arguments resulted in the rapid acceptance of the atomic theory of matter. His ideas were successful in explaining many of the chemical and physical phenomena of the nineteenth century. At about the same time, the concept of the molecule, an aggregate of two or more atoms whose properties are different from those of the individual atoms, came into prominence.

Scientific advances during the late nineteenth and early twentieth centuries resulted in the modification of these atomic ideas. Such scientists as Sir William Crookes, J. J. Thompson, and Lord Rutherford found that it was necessary to think of atoms as divisible into small, electrically charged particles in order to explain radioactivity and X-radiation. Today, many dozens of "ultimate" particles are known (hypothesized), although many phenomena with which we are directly acquainted are most conveniently explained by reference to atoms, electrons, and protons. The concept of the atom has grown from a very simple, indivisible atom into a complex intra-atomic structure whose details are not yet clearly understood.

Along with the division of the atom into fragments, the equivalence of matter and energy has become a tenet of modern science. The famous equation $E=mc^2$, which states that the energy of any given quantity of matter is represented equally well by its mass times the square of the velocity of light, was not derived from experiment. It was, instead, a consequence of certain theoretical propositions formulated by Albert Einstein in 1905 in order to make his theory of relativity mathematically rigorous.

It is impossible to formulate in one sentence an idea more significant than Theme 1, because of its explanatory power in all the scientific disciplines. It illuminates the depths of chemistry, physics, astronomy, and biology. The atomic bomb, radioactivity, the energy of the stars, the 103 elements—these different phenomena are all evidence of its thematic strength.

2. *The particles of matter interact with each other.* Themes 1 and 2 are closely associated. Matter, as we see it, feel it, and know it, is the totality of interactions between the particles of which it is composed. These interactions are believed to be responsible for our changing world of

time-space. The quick superficial answer to the questions, "What makes a ball fall?" "What holds a suction cup on the wall?" and "Why is a diamond so hard?" is "force." Three fundamental kinds of forces—electromagnetic, gravitational, and nuclear—have been accepted as valid ideas. Electromagnetic and gravitational forces may traverse vast distances. The former are frequently much stronger; the latter are weak, detected only in the neighborhood of large masses. The strong nuclear forces weaken rapidly with distance from nuclear particles, and appear to be insignificant in ordinary, daily interactions.

Children will probably not be concerned with nuclear forces, because electromagnetic and gravitational forces are sufficient to account for the natural events with which they will come in contact. Most events in the realms of physics, chemistry, and earth science are intelligible in these terms; it is even possible to depict, although imprecisely and qualitatively, the interactions within living systems. It is too much to expect children to understand what force is and how it acts, because no one really knows what force is or how forces affect bodies (or other forces) at a distance. Children are not ready for either philosophical word play or the operational definitions of physicists. They can, however, bring to the analysis of force and interaction a sufficient intuition and insight for a sound beginning.

The concept of interaction may be clarified by this example: The strength of the electric forces surrounding a charged body decreases at a rate inversely proportional to the square of the distance from the body. The forces of attraction or repulsion between charged bodies are much the same, whether they are the static forces which hold a balloon to a wall, the forces which maintain the structure of sodium and chloride ions in a salt crystal, or the forces which give water an "abnormally" high boiling point. The solubility of chemical substances is also dependent on the attraction of unlike charges (or, at least, on electromagnetic forces). The concept of attraction between oppositely charged bodies may not be "true" in the sense that it corresponds exactly to nature, but it is extraordinarily useful in making sense of happenings which, at first glance, are completely unrelated.

On the other hand, although gravitational force is not useful in explaining solubility, it makes possible analysis of the interactions of huge masses of matter such as the earth and stars. Scientists do not know how this force is created or how to control it, but the idea of gravitational force provides the explanatory scheme for predicting planetary movements, the rate of fall of bodies to the earth, and the period of a pendulum.

Few biological phenomena have been reduced to interaction of forces. The nesting habits of a robin, the characteristic leaf form of an elm tree, and the "struggle for existence" are examples of interactions which are still almost inexplicable. Many scientists believe that growth, behavior, and life itself will ultimately be explained and predicted in atomic and molecular terms. But we are far from this mastery of nature now, and predictions and explanations in the biological sciences lack the power and applicability of the theoretical structure of the physical sciences. Therefore, these life activities are said to be controlled by higher levels of organization, such as hormones, mitochondria, and genes. This situation is somewhat like the present status of quantum mechanics in chemistry. Quantum mechanics, an axiomatic, rigorously mathematical conceptual scheme which was first proposed in the 1920's, is theoretically capable of providing all the information from which the chemical properties of all the elements and compounds may be predicted. But the sheer complexity of atomic structure frustrates mathematicians, who (even with computer assistance) are unable to solve the necessary equations. Therefore, although it may be theoretically possible to predict the chemical behavior of matter from a knowledge of force interactions, it is not yet practical.

This theme of weak and strong interactions best fits the physical and the earth sciences, but it is also fruitful when applied to biological interactions between and within organisms on a supra-molecular level. Ecology, the study of the relationships of living things and their environment, is a maze of large and small interactions. Each plant and animal acts on its surroundings, and in turn is acted on. Deer multiply when food is abundant, but their predators also multiply; the rapid increase in number may cause death by starvation (and increased predation) as the deer destroy shrubs and girdle trees in their search for food. Man changes his world quickly and destructively, but he too is vulnerable.

3. *Because matter exists in time and space, and because the particles of matter interact, changes must occur in time and space.* Change is evident to all; some changes are quick, lasting but a moment; others are almost infinitesimally slow, scarcely begun in a millenium. Because change is built into our lives, it is a constant of nature. Themes 1 and 2 state that matter is composed of particles which interact with one another, either by attraction or by repulsion. These interactions must cause changes in position. Such movements in the dust clouds of the primordial universe are assumed to have caused the hydrogen of these clouds to heat up sufficiently to begin the nuclear reactions which form stars. Many astronomers believe that this process is continuously creating new star-matter.

This theme of change is expressed most magnificently in the agelong story of the birth (and perhaps eventual death) of our universe; but it is just as helpful in making sense of the Earth's history. The birth and decay of volcanoes, mountains, deserts—indeed, all the phenomena of geological transformations are clarified by this theme. It even reaches down to such modest backyard events as lawn erosion, the cracking of sidewalks, and the splitting of rock by frost.

4. *Matter exists in a variety of forms, arbitrarily classified by their complexity.* Man is a categorizing animal; he classifies whatever he observes into groups according to their common elements. Theme 4 makes explicit a necessary task in the investigation of nature. The first patterns which are found may be only structural similarities. Leaves, for example, may be compound, opposite, toothed, hairy; they may be simple, alternate, smooth-margined, and glabrous. Leaves exist in an almost infinite variety of forms within a species, merging imperceptibly from one to the next. Leaves on any one tree (e.g., sassafrass) may differ greatly. The taxonomist measures each leaf against a mental construct, an "ideal" specimen, which is the standard of comparison.

Inorganic matter may be classified according to the elements of which it is composed: silicates are compounds of silicon and oxygen; carbonates are built of carbon and oxygen. Such states of matter as solid, liquid, or gas, the state depending on the particular conditions of temperature and pressure of the substance, are also useful. There is almost no limit to categorizing. One of the controversies which embroil biologists is between the taxonomic "splitters" and "lumpers"—those who argue for many narrowly limited plant or animal species and those who prefer a few inclusive species.

Matter, living and non-living, may also be classified by its complexity. Elements are atomic aggregates; atoms combine to form molecules and, in turn, are structured of such lesser particles as protons, neutrons, and electrons. Molecules aggregate into larger masses—rocks, mountains, planets, and stars. Planets and stars form solar systems; aggregates of stars and solar systems are incorporated into galaxies.

These hierarchies are pyramidal: the base is formed of lower-level units from which higher units are derived; these units in turn blend with others still higher into a more complex aggregate. No scientific problems are solved by this sorting, for nomenclature does not explain; but each higher organization is a distillation of many specific properties into one or more generalizations which summarize its characteristics. Mention of an amoeba should evoke an image of an animal without a cell wall, with a contractile vacuole, and with protoplasmal streaming. This familiar picture is a synthesis of many individual bits of information which are collectively the amoeba. The name "amoeba" predicts no new and unusual properties.

Another kind of unit is not the sum of its constituent elements. It is a synthesis which has new properties. Air is composed of oxygen, nitrogen, argon, and a number of other elements. Table salt is more than sodium plus chlorine. Another example of this kind is the biophysical state of "amoebahood." It is naive to assume that the amoeba is the exact sum of its molecular relationships. The profound complexity of this "simple" life form is of a much higher order than the difference between sodium chloride and its constituent elements.

5. *The distribution and behavior of matter in the universe is often best studied statistically.* Predictability in science is an outcome of the scientific belief that the universe must be described in terms of probabilities. Physicists, for example, do not know the exact location of a particular electron in a particular atom at any instant of time. But they are quite certain that, given enough electrons, they can predict the position of these electrons according to a probability distribution; that is, they can assign a certain chance for electrons to be at a predetermined distance from the atomic nucleus.

Measurement of length is scientifically meaningless unless it is qualified. If the length of a table is given as 103.46 inches, this does not mean that the table is 103.46 inches long; the table length is probably somewhere between 103.45 and 103.47 inches. A large number of careful measurements will strengthen the probability that the length is very close to 103.46 inches.

In a different context, a species "type" is not the ideal, the harmonious blend of all specific characteristics, but merely a bench mark. No two specimens are exactly alike. They differ in their lengths, widths, thicknesses, number of teeth, and other identifying features. The "ideal" is therefore only a statistical concept from which all actual specimens diverge to a greater or lesser degree.

The importance of statistical understanding in assessing scientific work is sufficiently great so that it should be encouraged throughout school life. Every measurement (or almost every measurement) involves some uncertainty, and therefore some probabilistic divergence. It does not matter whether we struggle with a sub-atomic microcosm or a super galaxy, the uncertainties which are either introduced by our instruments or are already present force us to make a statistical evaluation of measurement.

6. *The interactions of matter tend toward equilibria in which available energy is least, and random distribution of energy is greatest; total matter-energy in a closed system is constant.* This theme is also statistical in its implications and its theoretical foundation. There is no known case in which interactions in a closed system violate this broad rule, but, of course, the absence of evidence to the contrary does not prove an assertion, particularly one which is so far-reaching. The organization of matter into aggregations of atoms is much less probable than is existence of isolated atoms or

atoms in small groups. In order for a combination of atoms to exist, work must be done to overcome the repulsive forces between the particles and to force and hold them together. The average energy available within the resulting combination as a result of the work performed on it is greater than that of the surrounding unpatterned (disorganized) environment. Matter which is at a higher energy level tends to return to a lower energy level, in which the individual particles move more slowly, are more scattered, and are therefore more disorganized.

Scientists believe that the sum total of all the energy and matter in the universe is conserved; that is, it is constant. This is merely a statement of the law of conservation of mass-energy, otherwise known as the first law of thermodynamics. The second law of thermodynamics asserts that heat energy is evolved in the interactions of matter; a part of this heat energy is inevitably lost to us; and, as a result, the total quantity of useful energy in the universe is steadily decreasing.

These degradation processes may be reversed in individual cases by taking energy from other sources; this, in turn, depletes still further the supply of accessible energy. Living systems build complex molecules out of simple molecules, which reverses the "normal" downhill drift of disorganization, but this occurs only because energy is continuously made available by respiratory and nutritional processes. In osmosis, the direction of flow is generally from high to low concentration. In living organisms, the direction of flow is frequently reversed, because energy is expended to make this "violation" occur.

The nature of these physical processes may be further illustrated by LeChatelier's principle, which states that a stress applied to a system in equilibrium results (if there is no equivalent counter-stress) in a shift which tends to minimize the stress. That is, in a system at one energy level, stress may be decreased by reducing the available energy. Consider the case of a rod balanced delicately on a fulcrum. The center of gravity of the rod is directly above the point on which the rod rests. If weight is added to one end of the rod, the rod dips, lowering the center of mass below the support point, thus reducing the potential (available) energy of the system.

The homeostatic equilibrium of living organisms, a delicate system of checks and balances which maintain the proper environment for living cells, is disturbed by the increased intake of carbon dioxide gas and a rise in acidity of the fluid bathing the tissues. The organism responds by a series of chemical reactions which decrease the blood gas concentration. If the resources of the organism are insufficient to decrease the carbon dioxide concentration, its life is imperiled, because the cellular environment has been disturbed. The energy potential of the organism is reduced because energy has been diverted to the task of removing the equilibrium-disturbing intruder.

It is impossible to overemphasize the importance of this theme of energy availability in the conceptual structure of science. The student who is scientifically literate has built this theme into his own cognitive structure, and, as a result, he understands how and why energy relationships provide the scientist with a point of view which makes sense of the world.

7. *Motion of the particles of matter is one of the major forms of energy.* Energy is defined as the ability to do work; work, in turn, is defined as the product of a force exerted through a distance. For more than a century, scientists have assumed that all matter is composed of particles in constant motion, and, as a result, that these particles possess energy. When molecules move rapidly at distances great enough from each other to dilute inter-molecular forces, they are said to be in the gaseous form. Because the particles are moving rapidly, the gas is highly energized and has the potential to do work in gasoline and rocket engines.

Energy exists in many forms, of which mechanical energy, the energy of moving particles, is but one. Other forms are electrical, heat, light, magnetic, and gravitational energy. Heat energy is a function of both the average velocity of the particles and of their total number. According to this, the kinetic model, a gas at low pressure may be at a high temperature (i.e., its molecules may be in rapid motion), but little heat energy is available, because there are relatively few molecules. Despite the contrary evidence of the senses, a block of ice may be hotter than an equal volume of steam, in the sense that many molecules of relatively low kinetic energy represent a total heat energy greater than that of a few rapidly moving molecules.

No matter what the source of the body's energy or its mode of storage, plant and animal tissues eventually convert this raw material into molecular motion. Energy from sugar metabolism, for example, is used up in cells in a bewildering complex of chemical reactions. It is this energy which gives muscle tissue its contractility and which enables nerve tissue to transmit an electric potential.

Electromagnetic energy, in the form of light waves or magnetic fields, is a product of the motion of electrons; in turn, electromagnetic energy induces electron movement in receptors. Radio waves generated by very rapid vibration of electrons in an antenna are detected because similar vibrations are induced in the receiver.

One of the classical assumptions of modern molecular theory is that at the temperature of absolute zero, some 273 degrees below zero Celsius, molecular motion ceases and the energy of motion thereby vanishes. (The Celsius temperature scale is now the approved name for what was formerly called the centigrade temperature scale.) Even so, potential energy at this temperature is conceivable, because particles are mass and therefore equivalent to energy.

In one form or other, energy concepts are deeply interwoven into most of the scientific phenomena encountered by children and adults. For example, the physical transformations of matter, its interactions, and the very characteristics which define matter are ultimately explainable by this (and the other) themes of energy distribution and equilibrium.

8. *The processes of the past are those of the present and the future.* This theme, like its predecessors, is axiomatic in the sense that it cannot be rigorously proved. It is different, however, because it is not an explanatory theme. The change in state of gas to liquid is explained by several of these themes, which collectively postulate a decrease in the average kinetic energy of gases as their temperature is lowered. At some particular temperature, the gas liquefies. Instead of providing an explanatory "fiction," this theme is an *opinion* that the order of nature is consistent. It is even more abstract than the other themes, because it is so far removed from the physical constructs with which we have dealt. While it is reasonable and logical to think of the present and past as a continuum, it is also possible to argue that our earth in its early history was governed by supernatural or other-natural rules of behavior. Those who look to the Bible for divine revelation and take its word as the literal truth do not accept the chemical, geological, and biological processes of diastrophism, erosion, and evolution or the evidence of rocks as a better explanation of the history of the earth and the origin of life.

The doctrine of "uniformitarianism," the belief that natural processes, past and future, are like those of the present, is one of the keys to exact description of our universe. The scientist rejects the possibility that magical or unfathomable forces helped shape our world, because he accepts a precept of maximum simplicity—the belief that all the phenomena of our universe are causally related to known forces. Of course, many physical events are neither completely known nor satisfactorily explained, but the scientist is confident that at some future time sufficient data or more potent theories will bring even these phenomena to terms. Scientists do not know why the dinosaur and saber-toothed tiger perished. They will probably never know as precisely as they now know why the passenger pigeon and the heath hen vanished. They are sure, however, that the explanation, complex though it may be, is reasonable and worldly. Recent research into the origin of life suggests the kind of primordial environment in which life may have evolved. Some researchers have perhaps overextrapolated the data, to infer the inevitability of life arising on any planet with similar conditions. Some astronomers have even hypothesized the existence of millions of planets throughout our vast universe on which life might evolve.

It is this intuitive commitment to the theme of uniformitarianism which justifies comparing lawn erosion with the formation of a river valley and the upheaval which marked the birth of the Rocky Mountains with the evidence of contemporary mountain building.

The themes – a reprise

These eight pervasive themes are significant declarations, but they are not all-inclusive; others of greater or lesser import may be added almost at will. In one form or other, these conceptions are the *permeating structural elements* of science; their conceptualization by children and adults at some meaningful level is one of the urgent goals of science education. They lead to explanations of the various phenomena of our environment in an economical and intellectually satisfying way. They are neither absolutes nor eternal verities. They *are* convenient hypotheses, whose interpretative strengths make possible consistent and logical explanations of natural experience.

The themes are not axioms conjured out of the cerebral air. Their strength lies in the fact that they have painfully evolved from centuries of observation and experimentation. Every scheme (principle, law, theory) of science depends in some logical way on these themes – but, in turn, the themes are operational *because* they were born out of the direct and indirect experience of countless investigators. The scheme which embraces the volume change of materials with temperature change (e.g., the expansion of a metal rod when heated) is explained by the assumption that materials are composed of molecules that are vibrating relatively slowly. When heated, the molecules of the rod, for example, are forced to move more rapidly, overcoming the molecular interactions which fix them in place and increasing inter-molecular distances. The rod, therefore, expands three-dimensionally. The equilibrium state of the rod after heating is the joint result of the added energy of the molecular interactions, which resist expansion, and of the tendency of the rod to relieve the applied stress (heat) by adjusting in such a way that the stress is minimized.

Without these simplifying themes, more intricate explanations must be proposed. The early nineteenth century theory of heat expansion assumed that heat was a fluid ("caloric") in which the particles of matter were embedded; this atmosphere, surrounding each particle, repelled other atmospheres. If the quantity of caloric increased, so did the repulsive interaction, and, therefore, the material expanded. This explanation, valuable though it was in 1820, failed to fit in with the physical knowledge of the mid-nineteenth century, and because it introduced too many complicating factors, it was soon abandoned.

No matter how modern scientists explain natural phenomena, their explanations must be ultimately reducible to the themes enumerated on page 169. It is for this reason that their incorporation into the intellectual beliefs of the child and adult is of the highest priority.

Process themes

The themes embody a part of the content structure of science. They are the intellectual scaffolding which conditions not only what scientists see, but what they expect to see. They are *not* the elements of process which have been frequently referred to, and whose mastery at appropriate stages is so important. These process elements are characterized in some detail in Chapter 1 and are summarized below to remind the reader that process is the essential counterpoint to product.

1. The data of science are most valuable when they are quantified.
2. Science is utterly dependent for its raw materials on keen observation and rigorous experimentation.
3. The validity of scientific hypotheses is tested by comparing prediction with reality.
4. Science is cumulative and self-correcting.
5. The "method of science" is a philosophical analysis of scientific research. It does not tell us what steps to take for scientific discovery.
6. The scientific endeavor is possible only when scientists adhere to the humanistic values of truth, freedom, independence, and tolerance.
7. Science is as much a point of view toward our universe as a study of its composition and behavioral laws.
8. Much of the content of science is indirect, inferential, and probable.

The schemes of science

An almost infinite number of conceptual schemes (principles, laws, and theories) of greater or lesser relevance to the teaching of science have appeared in print. Those listed are chosen because of their general acceptance and because of their illustrative and explanatory power.[4] They are examples of science as product. As objectives, they are less vital in comprehending the nature and meaning of science than are the themes. In a sense, however, they are tools for achieving this comprehension, and cannot be ignored.

I. *Biology*

1. Plants and animals are dependent on energy released from oxidation of food.
2. The properties which characterize the protoplasm of all living cells are similar.
3. Protoplasm is continually reconstructed in living organisms.
4. Chlorophyll-containing plants produce nearly all the available food of our world.
5. All living organisms must provide oxygen to their cells in order to obtain energy.
6. There is a maximum average size for each kind of plant and animal.
7. The carbon dioxide produced by both plants and animals in respiration is utilized by plants in the process of photosynthesis.
8. One of the characteristics of living matter is its ability to respond to environmental stimuli.
9. Chromosomal units (genes) of cells are the physical base for heredity.
10. Life forms vary, but variation itself is limited.
11. Life forms unable to cope with changing environmental conditions become extinct.
12. Taxonomic grouping of plants and animals is indicative of evolutionary relationships.
13. Environment modifies life forms; life forms, in turn, modify the environment.
14. The more complex forms of life are ultimately dependent for nitrogen on soil bacteria.
15. Most life forms alternate cyclically from periods of low to high population.

II. *Physics*

1. Liquids are only slightly compressible.
2. Bodies which are in rotation tend to move in a direction tangential to the rotational arc.
3. Pressure at any particular point in a liquid is the same in all directions.
4. Gases tend to expand to fill the available space.
5. Heating causes expansion in most materials, a change reversible on cooling.
6. Matter in vibration causes sound.
7. Waves striking a surface may be absorbed, reflected, or transmitted in any combination, depending on the material and condition of the surface and the angle of incidence.

8. A magnet always has at least two poles, which are surrounded by a force field.
9. Like electric charges repel; unlike attract.
10. Electrons flow along a conductor if available energy is decreased in the process.
11. Absorption of energy by electrons raises their energy levels.

III. *Chemistry*

1. The energy evolved in the decomposition of a chemical compound is equal to the energy required to form it.
2. Under comparable conditions of temperature and pressure, equal volumes of gases contain equal numbers of molecules.
3. The solubility of gases in liquids with which they do not react chemically is directly proportional to the pressure.
4. Ionic reactions tend to be very rapid.

IV. *Geology*

1. The earth is not perfectly spherical.
2. Approximately a dozen elements make up all but an insignificant part of the earth's crust.
3. The continents and ocean basins are in a state of equilibrium (isostasy).
4. Energy obtained from the sun is balanced by energy lost from the earth.
5. The circulation of water in the oceans is caused by density differences and surface winds.
6. Radiation striking the earth's surface is absorbed and converted into molecular motion.
7. The kinetic energy of flowing water gives it erosive strength and its ability to carry solid and dissolved substances.
8. The earth and moon form a dynamic, interacting system.
9. Planets which are sufficiently large may hold an atmosphere.
10. The sun is an average star.

For further study

1. What is the role of specific scientific information in the nurture of "the inquiring mind"?

2. List and describe some of the behavioral objectives in the water-glass-card experience presented in Chapter 4.

3. Contrast the adequacy of these statements as behavioral objectives:
   (a) To be able to formulate a simple scheme for classyifying leaves.
   (b) To show an appreciation for the work of the scientist.

4. Rewrite these statements as behavioral objectives:
   (a) To appreciate cause-and-effect relationships.
   (b) To be aware of the need for practicing conservation.
   (c) To be able to use mathematics in understanding science.

5. What are the weaknesses of the "block-and-gap" curriculum?

6. Why are the themes of science concerned mainly with the physical rather than the biological sciences? (See Bentley Glass' vigorous criticism of the original themes in "Theory into Action—a Critique," *The Science Teacher*, 32: 29-30, May 1965.)

7. Formulate a theme which is specifically biological. What arguments can you propose for including it with the other themes?

8. Justify or criticize each of the eight process themes.

9. Draw up behavioral objectives for at least one scheme in each of these categories: biology, physics, chemistry, geology.

References

1. Einstein, A., "Autobiographical Notes," in Paul A. Schilpp, ed., *Albert Einstein: Philosopher-Scientist* (New York: Harper & Row, 1959), p. 17.

2. Rogers, Eric M., "Science Courses in General Education," in Earl J. McGrath, ed., *Science in General Education* (Dubuque, Iowa: Wm. C. Brown, 1948), p. 16.

3. Adapted from *Theory into Action in Science Curriculum Development* (Washington, D. C.: National Science Teachers Association, 1964), p. 20.

4. These schemes are taken from a much longer list in Circulars OE-29025A and OE-29026A, published by the United States Department of Health, Education, and Welfare, Office of Education.

6

The new elementary science

The teaching of science is at the threshold of a dramatic new era. For the first time, a massive effort by scientists and science educators to design entirely new curricula in every field of science has been made possible by adequate financial support. The first curriculum to rethink, rewrite, and revive science as both process and content was synthesized by the Physical Science Study Committee, organized at the Massachusetts Institute of Technology by the noted physicist Dr. Jerrold R. Zacharias in 1956. Dr. Zacharias and his colleagues were appalled by what they regarded as the failure of conventional high school physics instruction to present modern physics as a way of gaining an insight into physical phenomena:[1]

> The aim was to present a view of physics that would bring a student close to the nature of modern physics and to the nature of physical inquiry...(The committee sought to transmit the human character of the story of physics, not simply an up-to-date codification of the findings. The student should see physics as an unfinished and continuing activity. He should experience something of the satisfaction and challenge felt by the scientist when he reaches vantage points from which he can contemplate both charted and uncharted vistas....)

The Physical Science Study Committee, supported financially by the National Science Foundation and private foundations, has created an entirely new physics curriculum which, in 1964–1965, was in one form or another being taught to approximately half of the high school students in the United States who were enrolled

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in physics courses. An original laboratory program, numerous motion picture films, special laboratory apparatus, collateral readings, and a comprehensive testing program reinforce the newly written and frequently revised textbook. The PSSC has also pioneered in teacher education by subsidizing the in-service training of approximately eight thousand high school teachers in summer institutes throughout the nation.

The PSSC has thus delineated the guidelines which direct this revolution in science teaching: (1) A group of leading scientists, classroom teachers, and educational specialists are paid to meet jointly for long periods of time in order to develop texts, laboratory activities, audio-visual aids, and tests. (2) These curriculum materials are tested in the classroom by selected teachers and classes throughout the United States. (3) These "experimental" teachers are specially trained for their task in summer or in-service institutes. (4) Teachers periodically report on progress and lack of progress to the program planners so that suitable revisions may be made. (5) After several years of field trials, an experimental edition incorporating the revisions is commercially published for all school systems that desire to use it. (6) Additional revisions are made as difficulties and new problems arise and the evaluative feedback from expanded classroom teaching flows in.

Although new programs do not always follow every step of this sequence, they invariably include experimental trials. This pre-testing is a significant departure from past efforts at curriculum revision. Some of the major upheavals in science curricula have been analyzed in Chapter 3. Almost invariably, they were *ad hoc*, part-time creations of individuals or small groups. Composed of arbitrarily selected and unevaluated content and experiences, they were imposed on teachers untrained in their content and methodology. The new programs, on the other hand, vigorously seek teachers who are in sympathy with their goals and methods, and by means of in-service education and continuous feedback, they strive to generate practical, effective science instruction.

Soon after the PSSC had shown the feasibility of curriculum reform, similar programs were begun in chemistry, biology, and earth science for high school students. Following immediately on their heels have come at least eight major projects in elementary school science. Even before this movement in elementary science, mathematics teaching in the elementary school had begun to be affected by the University of Illinois Committee on School Mathematics, the School Mathematics Study Group, and the Syracuse University-Webster College Project.

What is particularly noteworthy and disturbing about these projects is that they have originated from outside the conventional school structure. Their origin and impetus came from noted university scientists and mathematicians whose direct entrée to the National Science Foundation provided the financial support essential for success. It is improbable that the multitude of science and mathematics educators who recognized deficiencies in the teaching of their specialties could have successfully initiated programs of this magnitude, because of the financial and consultative limitations which confronted them. One weakness of these programs is that most professional educators are barred from direct participation in planning and in writing curriculum materials which *they* are ultimately expected to approve and supervise. For example, few institutions which prepare large numbers of teachers for the elementary schools have been invited to participate in preparing teachers trained to teach these programs. Nor have these institutions been successful in obtaining the kind of information which they need, nor have their personnel been invited to attend "training institutes" so that they will be prepared to introduce new materials into their curricula. Other serious weaknesses exist. How, for example, are school systems to choose the most desirable program? None of the elementary-science projects is completed in the sense that a unified, thoroughly tested curriculum has been commercially published, although several will soon be ready. Schools must allocate longer periods of time for science instruction, in addition to devising a kind of continuity with secondary schools which has not yet been planned. The multitude and diversity of curriculum projects in the elementary sciences therefore poses a formidable problem to school systems. Despite the hypothetical desirability of a unified K–12 curriculum in each school system, its feasibility is doubtful, because of the high transiency of the school population. Also, whether or not the K–12 curriculum in science is feasible, unified modern curricula have not yet been tested, and their successful adoption by schools lies in the future.

The fact that they are founded on the processes of science—observation, description, hypothesizing, and interpretation—rather than on knowledge of scientific facts and laws is likely to aggravate these problems. Evaluation of the *knowledge* component of science is not difficult. Objective questions and written work that test children's understanding of buoyancy or air pressure are easy to formulate. It is much more difficult to test how well children can hypothesize, plan ways of testing these hypotheses, and interpret data. Evaluative criteria, to be meaningful, must be in terms of the specific behavioral changes which are sought. That is, if children learn a fact or a skill, they should be able to display this learning—their behavior patterns should change. The objectives for science programs should be stated as behaviors which students can demonstrate—if they have learned them. These statements have not been prepared except in the AAAS program, although it is probable that the other projects will soon turn their attention to the formulation of practical behavioral objectives.

One of the current criticisms of the new programs is that their goals have no relationship to the goals of the elementary schools, but are subject-oriented instead. As Goodlad puts it, "Ends and means frequently become hopelessly entwined: to learn the subject is the end; learning the subject is the means."[2] Because no statement of objectives for both traditional and new science curricula is accepted, their relative effectiveness in attaining goals cannot be compared. Therefore, it is meaningless to claim that one or the other is more effective in elementary school instruction. (The majority of the new programs are unique in their commitment to Inquiry. Because their content and methodology are purposefully planned to give children experience and skill in finding out for themselves, it is probable that they are far more effective than conventional instruction in attaining this particular objective.)

Other problems should be mentioned. Many programs are tested in communities which are not representative of the total school population, and the generally favorable results obtained with middle- and upper-class children may not emerge in the large city schools. Teachers who conduct test programs are often specially trained, and with the enthusiasm of pioneers, strive diligently to obtain good results. It is possible that after thousands of teachers and children have begun these programs the desired results will not be achieved, because the teachers will no longer be closely supervised by the groups which produced these curricula. The history of science teaching reveals many instances in which enthusiasm and interest of a few teachers in a particular methodology or subject has produced electrifying results; yet unmotivated or untrained teachers who followed in their footsteps fell quickly into mediocrity. It is clearly impossible for more than a handful of teachers to receive direct instruction from the designers of a project. It may well be, however, that reform will founder on the rocks of misunderstanding and disinterest if this kind of "indoctrination" is not incorporated into science methods courses in colleges that prepare teachers. The problems which still confront the "new" mathematics in elementary schools suggest what may be in store for elementary science.

A number of projects have anticipated this difficulty. They have prepared manuals, some in excruciating detail, to orient teachers to the themes of the program and to specify, in sequence, what and how to teach. In their anxiety to assist teachers, they may repeat the erroneous methodology of early Object-Lesson and Nature-Study manuals. That is, suggestions to the teacher may become *the* way to teach. It is ironic indeed that scientists who bitterly criticize educational methodology and methods courses, which they contend are focused on "how-to-do it" and not on content, have produced teaching aids which are even more method-centered.

Despite these criticisms, there is no doubt that the future teaching of elementary school science will be heavily weighted with this new process content. These curriculum projects are unmistakably significant movements in the right direction, which is to teach science because it provides immediate opportunities for children to learn what science is, how it grows, and how scientists work. Each program has published preliminary, tested materials and is supplementing and revising them. There is now a large body of richly suggestive material which has been tested in many classrooms and written and rewritten so extensively that school systems can now adopt much of its content. Many of the fundamental ideas in science have been restudied; new and practical demonstrations and experiments have been prepared; kits of laboratory equipment and audiovisual aids may be purchased. In addition, the new work incorporates the lessons of their experimental origin so that the classroom difficulties which children experience in thinking and in manipulating are incorporated into the teacher's text. The insight of scientists, paired with the skill of experienced classroom teachers, has given the educational world a veritable treasure of science-teaching knowledge that was previously unavailable.

In this chapter, seven of the most significant and characteristic of these elementary-science curriculum projects are analyzed in terms of their stated purposes, content, methods, and evaluational procedures. The seven which are chosen embody certain common features, the most important being the centrality of scientific process. For the purposes of discussion, they may be divided into three approaches. The first approach is concentration on one science as an exemplar of scientific process and content. The University of Illinois Elementary School Science Project, under the direction of Dr. J. Myron Atkins, falls in this category, as does, to a lesser extent, the University of California (Berkeley) Science Curriculum Improvement Study, directed by Dr. Robert Karplus. The former is a course in astronomy (and the necessary mathematics); the latter begins with physics concepts and then branches into biology and chemistry. The second approach is the more or less simultaneous preparation of a number of discrete units of study in one or more of the sciences. The Elementary Science Study (an outgrowth of the original Physical Science Study Committee), and the School Science Curriculum Project, directed by Richard Salinger at the University of Illinois, follow this approach. The third approach is a unified curriculum for the elementary grades which includes content from all of the sciences. The American Association for the Advancement of Science Commission on Science Education, the Minnesota Mathematics and

Science Teaching Project (MINNEMAST), and the Elementary School Science Project at Utah State University, directed by Dr. John K. Wood, represent this type.

These seven are by no means all of the current research projects in the teaching of elementary science, but they are a representative sampling. We wish to point out that the extracts from these curricula, which are reproduced with special permission, are in every case taken from preliminary editions. The final commercial versions will differ in many ways, but we are confident that their goals, treatment, and style will be unchanged, and that these preliminary materials are therefore representative.

The single-science approach

University of Illinois Elementary School Science Project

The science of astronomy was chosen by the originators of this project because they believed that astronomy exemplified to an unusual degree how physical, chemical, and mathematical concepts can be integrated in classroom instruction. They argued that conventional science in the elementary school has omitted the investigative processes of astronomers, by which the facts in science texts have been discovered, and has neglected modern interpretations of the universe and of evolutionary theory. The discipline was taken as the model for writing the preliminary textbooks. There has been no attempt to create a distinctive teaching methodology; teachers are not given a full set of suggestions for implementing this program. Evaluative instruments have not been constructed in order to find out how effective teachers are with these new texts. Teachers interpret their teaching mandate according to their own conceptions of instruction. Both Inquiry-oriented and traditional teachers report that these materials are suitable for their classes.

The texts present astronomical and mathematical facts and ideas in a predetermined sequence, which has been chosen by astronomers and science educators:[3]

> Emphasis ... is on careful development of a conceptual sequence that highlights rational argument rather than conclusions, and is also on the intellectual power of a few pervasive ideas rather than description of loosely connected facts and phenomena.

It is important to remember that the particular facts and ideas have been selected by astronomers because of their pertinence to astronomical thought, although the sequence which has been chosen was not completely determined by astronomers. It is probable that this series is the most accurate and up-to-date astronomy series that has been written for children.

These books have been tested in hundreds of elementary school classrooms by fifth- to eighth-grade teachers who have not received special training. In the year 1964–1965, 177 teachers were using the complete materials, and 200 more were using some of them. The course was being taught in St. Paul, Minnesota; Sacramento, California; Norwalk, Connecticut; Orlando, Florida; and Portland, Oregon.[4] Each book takes approximately 2½ months, the exact time varying with available time and the grade and ability level of the children. The Elementary School Science Project does not expect any class to complete more than two books a year. The six books now prepared, several of which are now in a third or fourth trial edition, are:

> Book 1, *Charting the Universe.* Measurement of distances in the universe, the earth's shape and size; the inverse-square law of light intensity as a tool by which astronomical distance is measured.
>
> Book 2, *The Universe in Motion.* The two great conceptual models for interpreting the motions of the planets and stars—the geocentric and heliocentric theories.
>
> Book 3, *Gravitation.* The important concepts of mass, gravitation, force, acceleration, and velocity.
>
> Book 4, *The Message of Starlight.* How astronomers obtain significant information about the chemical composition of stars from spectroscopic analysis of starlight.
>
> Book 5, *The Life Story of a Star.* The evolution of stars and stellar similarities and differences.
>
> Book 6, *Galaxies and the Universe.* The galaxies and other objects beyond the Milky Way.

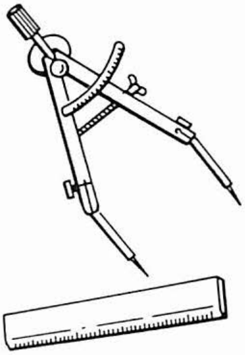
Book 1, *Charting the Universe,* is analyzed as an exemplar. It is composed of seven major chapters:

1. The Shape of the Earth.
2. Lines and Angles (Units of measurement and methods of measuring geometric figures).
3. Charting on the Earth (Methods of making measurements on the earth and of measuring distance to the moon.)
4. How Big? (Measurement of angular diameter.)
5. Charting the Solar System (Scale models and size of the planets.)
6. To the Stars (Light, the distances to the stars, and measurement of distance by the inverse-square law).
7. A View of the Universe (The Milky Way galaxy and other galaxies.)

The content is presented in a straightforward, relatively sophisticated fashion, contrasting sharply with conventional elementary school astronomy.

The extract presented below is typical of the approach and content:[5]

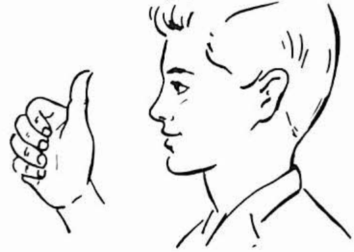
Chapter 4: HOW BIG?



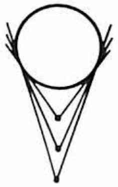
How big is the moon? How far is it through the moon? What is the moon's diameter? We haven't yet landed on the moon to measure its size in the same way we measure the earth. We shall have to try something else.

APPEARANCES

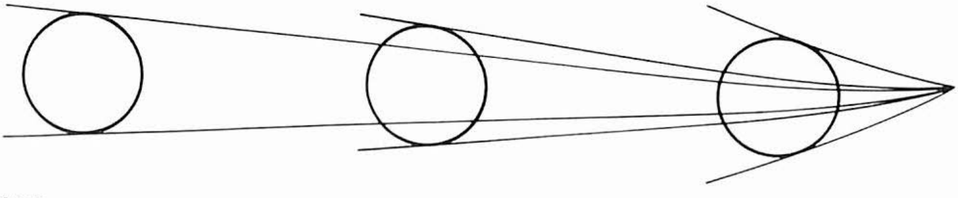
Let's start by distinguishing betweeen how big an object *appears* and how big it actually is. Hold your thumb near your eye so that you cannot see your teacher's head. Your thumb can hide him completely. Yet your thumb is certainly smaller than the teacher's head. Hold up a penny so that it exactly covers your classroom clock. Now hold the penny a little closer. What do you notice? Now hold it a little farther away. The apparent size of an object changes according to its distance from you.



How can we tell each other the apparent size of an object? Is it useful to say that the moon is two inches across?



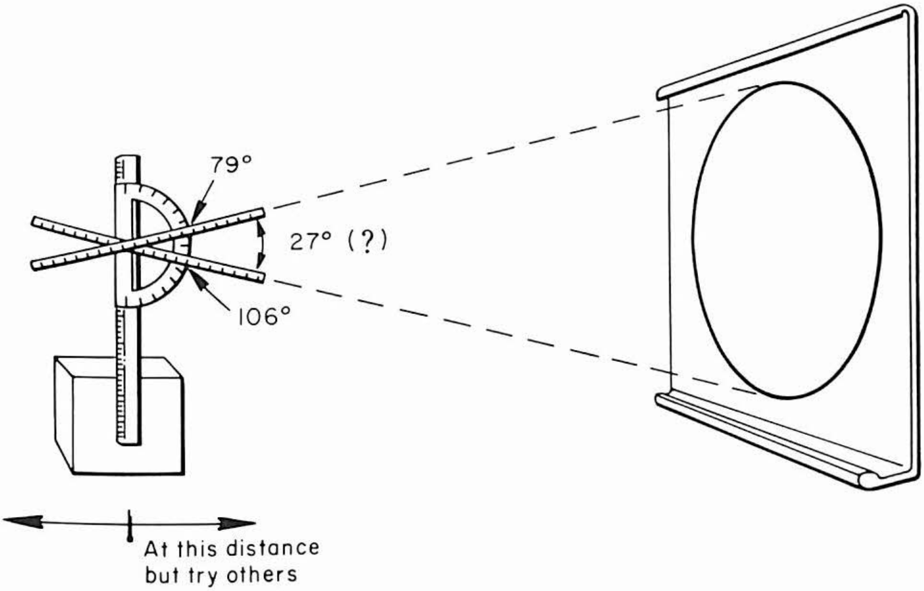
Put a penny or some other small round object on a piece of paper. Place a dot near one edge of the paper to represent the point from which you sight at the penny. Draw straight lines from the dot to each side of the penny. Place the penny at several different distances and continue the same activity. How does the angle change for different distances?



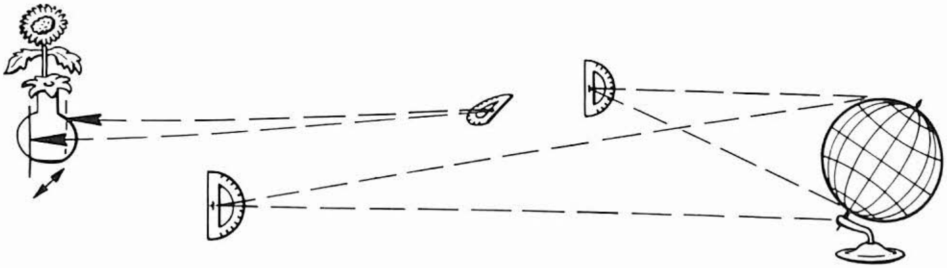
The true size of the penny does not change, but the angle does. The angle the object makes from where we look at it is the *angular diameter.* When we say apparent size, we mean angular diameter. The angle changes as the distance changes.

MEASURING ANGULAR DIAMETERS

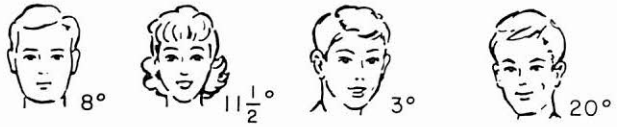
Fasten a protractor with a movable sighting straw to a ruler just as you did when making the range finder. Tape the ruler upright on a box. Draw a large circle on the chalkboard. Sight through the straw at the bottom of the circle. Read the protractor.



Now sight at the top of the circle and read the protractor again. The angular diameter of the circle is the difference between the two readings. Maybe you got 76° for the bottom and 98° for the top. Then the angular diameter of the circle as seen by you is 22°. Practice measuring the angular diameters of several objects in the room.

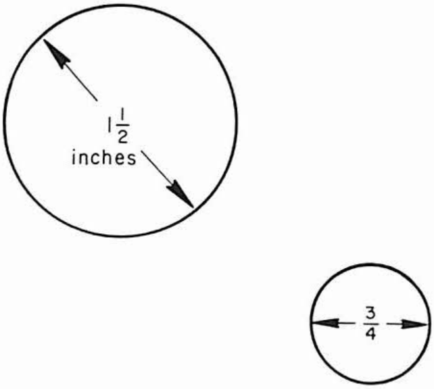


Set a globe in the front of the room. Measure its angular diameter. Compare answers obtained from different places in the room.



Globe : Angular diameter

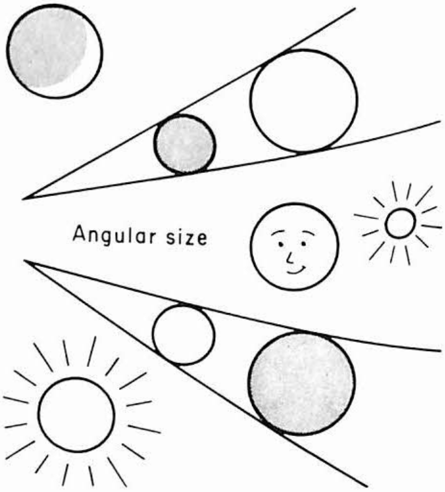
Astronomers measure angular diameters in a similar way. They use more accurate protractors and sighting devices, but the method is the same.



Make circles like these on a separate sheet of paper. Cut them out. On another piece of paper, draw two lines which intersect to make an angle. Put the smaller circle between these lines until it just fits. Can you find more than one place where the circle will just fit? Put the larger circle inside. Does it fit at the same place? Closer to or farther away from the vertex? When you place in the circles so that they just fit, how do the angular diameters compare? How do the true diameters compare? Repeat the activity using a smaller angle. Do the circles fit at the same distance from the vertex?

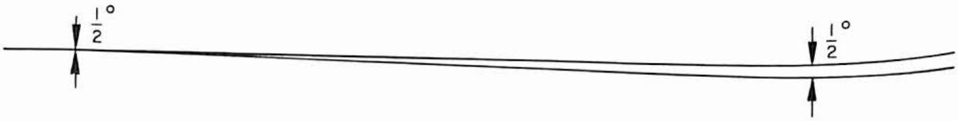
You demonstrate several ideas in this activity.

1. Objects with the same angular diameter are not necessarily the same size.
2. Angular size decreases as the distance to the object increases.
3. Angular size depends both on distance and true size.



Each one of these ideas is important. Even though the sun and moon have about the same diameter, one-half degree, the first idea shows that the sun and the moon are not necessarily the same size.

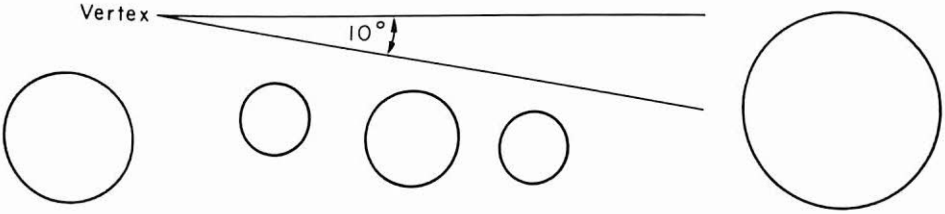
The other ideas help us to determine the true size of the sun and the moon. If you know the angular diameter and the distance to an object, the object can have only one size.



PROBLEMS

Find the answers to these problems by using scale drawings.

1. The angular diameter of a marble is 10° and its center is five inches from the vertex. How big is the marble?



2. Suppose a ball is three inches in diameter and makes an angular diameter of 10°. How far is the ball from the vertex?

Sometimes you can make measures that help you determine the size of an object without actually knowing the angular diameter in degrees directly.

Each volume of this series is introduced by a short chapter whose function is to arouse interest and to orient children to what is to come. This introduction is followed by a closely written factual narrative in a conversational style, incorporating some firsthand activities, illustrative drawings, and frequent questions and exercises, whose answers are not to be found in the text. Helpful suggestions and comments to assist the child in answering these questions and completing the exercises are frequently given.

Method: As previously indicated, a methodology is not proposed. Teachers are free to use these books in whatever way they choose. Some Inquiry procedures are included, but Inquiry learning is not a specific goal. Results in trial schools have been favorable, and the director of this project has concluded that older elementary school children are able to learn successfully what is taught. It is interesting to note that, despite some reservations by teachers that they were inadequately prepared to teach this particular content, their scientific training seems to have made little difference in the results.

Evaluation: Objectives have not been formulated as behavioral change, and it is not possible to assess the real achievement of the project according to this criterion. Children's interest in astronomy is high, and teachers are reported to be enthusiastic. Evaluation is primarily by means of reports from volunteer teachers. However, observational scales have been introduced in order to evaluate affective outcomes.

These six texts are not a complete astronomy series. For example, there is little about the planets and their satellites, in contrast with the mass of information about the solar system in elementary science texts. There is no feasible way of determining the effect on learning of missing elements in the sequence, nor has the effectiveness of these books been compared with either subject matter or process learning arising from conventional instruction.

The Science Curriculum Improvement Study (The Berkeley Program)

The goal of the Science Curriculum Improvement Study is to build the foundations of scientific literacy by providing primary school children with the opportunity to observe and to manipulate many different natural phenomena and by introducing them to the analytical regime which scientists use in manipulating these phenomena.[6] The overall curriculum design is predetermined by the structure of science and by the preconceptions and the level of maturity which children bring to it. Short-term activities (e.g., a week's work), concentrate on discovery and elucidation of scientific concepts.[7]

Although the completed materials will eventually encompass grades K–6, the project was begun with materials appropriate for primary-level children, avoiding a preconceptional rigidity of conceptual and experimental placement. The individual themes and activities, which are proposed by a staff of scientists and educationalists, are tried at several different grade levels.

The content of the four published manuals and of the additional trial material is primarily physical. The manuals published thus far are:

1. *Material Objects.*
2. *Variation and Measurement.*
3. *Interaction and Systems.*
4. *Relativity of Position and Motion.*

These manuals elucidate in an untraditional way the scientific modes of thinking about scientific phenomena. *Material Objects* is focused on the recognition and identification of material objects by means of properties and effects on one another, and by the ways in which they may be classified. *Variation and Measurement* deals with variations within populations, units of measurement, and conservation of volume. *Interaction and Systems* concentrates on more comprehensive ways of grouping and on the interactions of objects in systems. *Relativity of Position and Motion* discusses relativity, as well as symmetrical and asymmetrical spatial configurations.

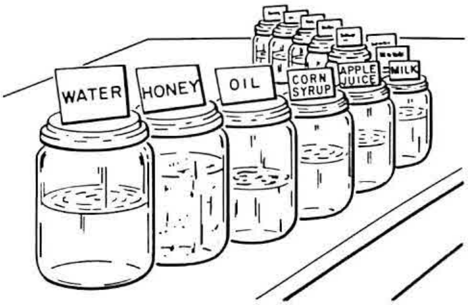
The expository style is illustrated by extracts from *Material Objects*, in which children are led to sort samples of liquids into groups by their external characteristics, by their miscibility in water, and finally according to their rate of flow.[8] These three lessons are followed by lessons on sorting powdered samples by such criteria as color, texture, taste, and miscibility with water. Prior to these lessons, children were given five lessons on observing objects and thirteen lessons on sorting such objects as buttons, nuts and washers, leaves, minerals, and metals.

EXPERIMENTING WITH MATERIAL OBJECTS

Lesson 19. SAMPLES OF LIQUIDS

The study of samples of liquids extends the concept of material objects for the students. It makes possible the introduction of experiences with miscibility and viscosity. You may find it a little strange that samples of liquid are considered as material objects in these lessons. You might think of the water in a glass as a "piece of water." If one then pours some water out of the glass, the water remaining in the glass is a different object. It is a smaller piece of water. You will introduce the pupils to the study of samples of liquids that have interesting properties.

A set of liquid samples in baby food jars is brought to the classroom by the teacher. The set of liquids is contained in thirteen baby food jars, each filled with one of the following liquids: honey, water, corn syrup (clear), molasses, motor oil, household oil, apple jelly, cooking oil, apple juice, liquid starch, condensed milk, white liquid paste, and vinegar. Attached to the cover on each jar is a stiff card on which is written the name of the liquid in the jar. For this lesson the jars are capped and should be left that way.



Hold up an empty baby food jar and ask the pupils to tell you about it. They will probably mention that the cover is metal, the jar is round, it is made of glass, it can be seen through, etc. Ask the children whether the jar is empty. They may or may not mention the air in the jar, but this is not critical to this lesson. If they mention the air, discuss it as an object contained in the jar. If the air is not mentioned, put some water in the jar and direct their attention to the sample of water in the jar. Emphasize that in this lesson when they describe the samples displayed they will be concentrating on the liquids inside, not on the jars.

Invite a child to come to the displayed set of samples of liquids. Ask him to choose some way to sort the samples of liquids into two groups. As he carries out this sorting, permit no discussion of how he is sorting until he has completed the task. Either ask the pupil how he sorted his samples of liquid, or allow the class to try to decide how he sorted his samples. Repeat this activity with other pupils. Some children may simply put half in one group and half in the other. Others, however, will probably sort by some property of the samples. For example, one may put all those he can see through in one group and all those he cannot see through in the other group. Others may sort into one group those which are colorless like water and into one group those which have color like honey. Record their use of these criteria or any others related to the properties of the liquids.

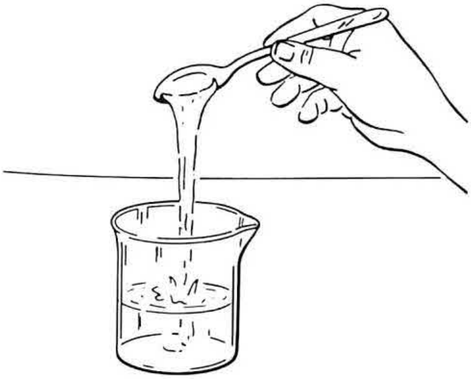
Page 43 in the student manual is now used. Place the sample of water on a separate part of the table or desk on which you have the set of samples. Compare each sample in the list on page 43 to the water. As you or one of the children places the sample next to the sample of water, each pupil should decide whether the sample is colorless like water. If it is not he should put a loop around the name of that sample. Encourage the children to make their own decisions.

Lesson 20. MISCIBILITY

The sorting in lesson 19 was based on properties observable without opening the jars. Ask the pupils what else they might find out about the liquids if you let them open the jar. They may suggest tasting or feeling them. The tasting should be discouraged, but the feeling of the liquids can be used as a class activity. A possible sorting would be to separate those which feel oily or greasy from those which do not feel oily. Perhaps one of the children will suggest mixing some of each sample with water. If not, you might suggest it and then place another jar half filled with water in front of each liquid sample. Ask the children to turn to page 44 in the student manual and then have one child come up and pour some of the first liquid into the first jar of water. Give him a wooden popsicle stick and ask him to mix the contents of the jar into which he poured the liquid. Allow the contents to settle and then have the entire class observe the results and record their observation on page 44. Repeat this operation with a different pupil for each of the thirteen liquids. Afterwards compare the observations made and see whether the different members of the class agree. Let the children discuss the value they see in a water-mixing test as a method for sorting liquids. Please make a record of their reactions.

Lesson 21. VISCOSITY OR RATE OF FLOW OF LIQUID SAMPLES

Place a set of the thirteen open jars of different liquid samples in front of the class and pose the following question: "If I turned all of these jars over at the same time, which of the liquids would reach the floor first?" After you contain the enthusiasm developed by the possibilities suggested by this question, admit that you do not plan to do this experiment. Ask the pupils how they think you could find out which of the liquids would pour faster than the others. Try out any suggestions the students have which are possible and plausible in the classroom. Have several spoons on the desk. Either one of the pupils or you may suggest that a spoon be used to pick up some of the liquid in a jar. Then you can drop it back into the jar and observe how quickly it runs from the spoon to the jar. Allow pupils to come up to the set of liquid samples and have at least one of them carry out this experiment for each of the liquids.



Based on their observations, the students should separate the liquids into two groups: one group which runs fast into the jar like water, and one which runs slowly into the jar like honey. Turn to page 45 in the student manual and repeat the experiments. This time have two children do the experiment for each sample. One uses the sample and the other uses water. As the class observes each experiment, they complete page 45 for that liquid. Afterwards compare the observations made and see whether the members of the class agree. Repeat the experiment for any liquid on which there is serious disagreement.

Lesson 22. SORTING POWDERED SAMPLES BY COLOR

Lessons twenty-two to twenty-five are intended to develop the ability to observe and to describe samples in powdered form. They deal with substances with which most children have had considerable sensory experience long before they come to school. All of them have used sugar and salt. If they have participated in food preparation, they have probably seen, felt, and tasted the other substances. Their awareness of the properties of the substances is likely to be entangled with their notions of use (sugar on cereal, salt on meat, etc.) rather than to be focused on the more intrinsic aspects.

In these lessons you ask the pupils to note distinctions in color, texture, and taste among substances that superficially appear quite similar. They are also asked to observe what happens when these different substances are combined with water.

Method: Specific directions to the teacher are supplemented with helpful comments for all activities, so that he may be fully oriented. This information helps the teacher to understand what the SCIS is attempting to accomplish both for the program as a whole and for each lesson. A considerable fund of specific scientific information is also included in order to provide teachers with more knowledge than most possess. For instance, in *Interaction and Systems*, before the concepts of change are introduced in the second chapter, teachers are given this information:[9]

> The idea of change, that things do not remain the same, is deeply intuitive. The change may occur in the properties of the objects involved or in their arrangement relative to each other. Sometimes you and your pupils may observe change in only one of the interacting objects. The scientist, however, believes that some changes are taking place in the other object, even though they may be hard to observe. When . . . the scissors and paper interact . . . the observed change is the cut paper. Actually something is happening to the edge of the blades of the scissors, though this is difficult to observe.

Detailed suggestions are provided:[10]

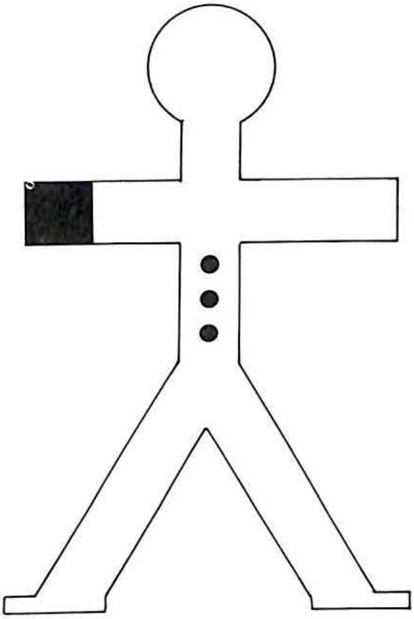
> The course provides for many kinds of activities: teacher demonstrations, pupil experiments, reading, interpreting illustrations, discussion, and so on. We have tried to arrange for some alternation among these. By using the pupil manual and by repeating some lessons as you feel necessary, you can adapt the course to your pupils' needs.
>
> Much of the work is designed to broaden the children's background of experience. Let them look again and again if their initial curiosity is not satisfied after one opportunity to observe. We should like to ask you, however, to refrain from drawing conclusions from the experiments. If the children do not seem to "get the point" of a lesson, be patient. Very few experiments lead to a single conclusion. It is the cumulative impact of many experiments and observations that persuades eventually.
>
> Let us now discuss the tendency of teachers of science to try to tie things up in a neat package every time a new experiment is performed. At the end of the period, teachers feel they should summarize what has happened during that period. This is such a common tendency among teachers that we have given it a name, Lysiphobia—the fear of leaving "loose ends." If you have this common malady, you will find it hard to resist the temptation to summarize. Nevertheless, try. Leave some loose ends. These you and the children will pick up during some future experiments. The children's recognition that the old and new experiments are related is a discovery which will give them a thrill and increase their interest.

Although classroom teaching concentrates on observation and direct experience, there is a supplementary manual which is usually read to the children. Teachers are cautioned not to "replace" experiments with the manual because classroom teaching and participation in activities and experiments is the "core" of classwork. This manual,

(Continued on page 203)

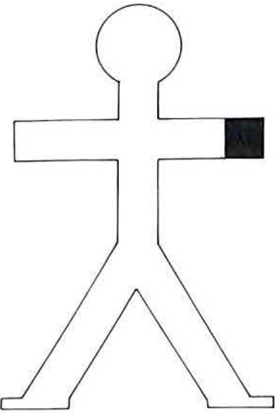
MEET MR. O

This is a picture of Mr. O.
Mr. O's right arm is painted.
Mr. O has buttons in front.

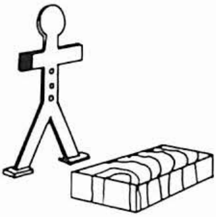


Mr. O helps us to think about experiments.
Mr. O is an observer.

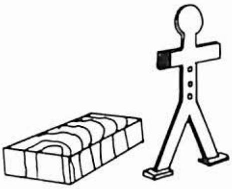
Mr. O is not like a person.
Mr. O thinks he is the most important thing in the world.
He thinks everything goes on around him.



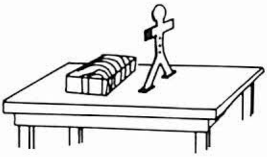
This Mr. O reports,
"The block is in front of me and close by."



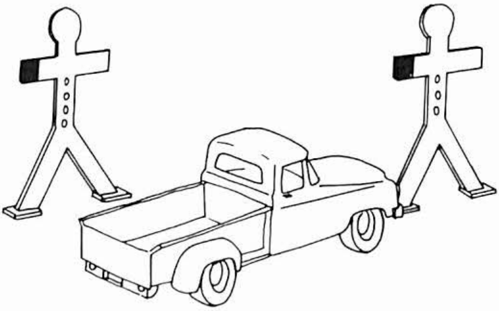
This Mr. O reports,
"The block is behind me and close by."



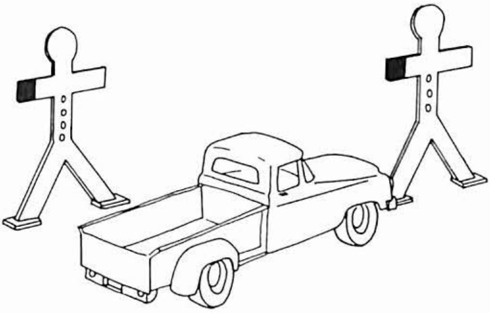
This Mr. O reports,
"The table is under my feet."



Sometimes we think of many Mr. O's.
Here are two Mr. O's.
They observe the toy truck.



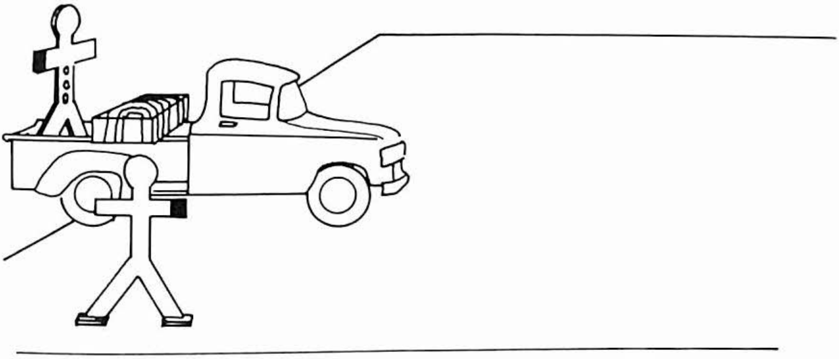
One Mr. O reports, "The truck is in front of me."
The other Mr. O reports, "The truck is on my right."



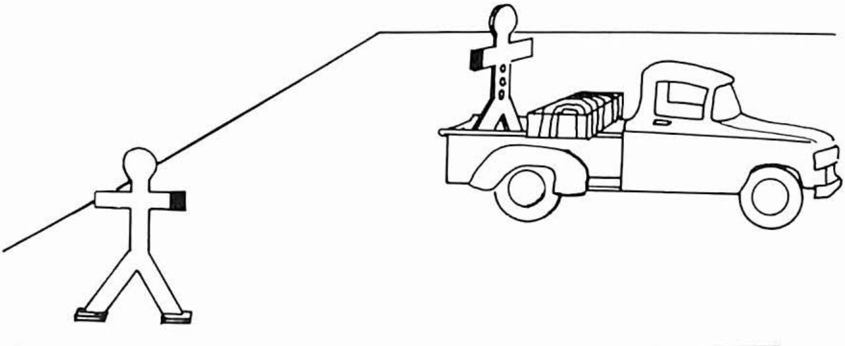
Do two Mr. O's always make the same report when they observe the same system?

Here is a picture story of your experiment.

Beginning



End



Two Mr. O's observe the block.
Mr. O on the table observes the block.
Mr. O on the truck observes the block.

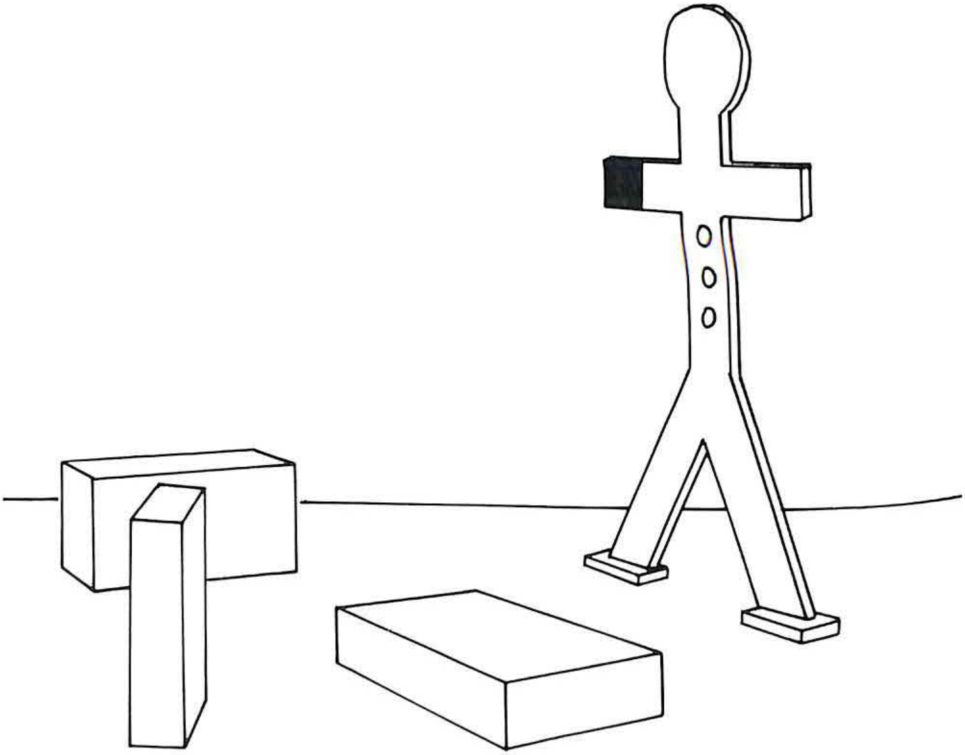
At the beginning, Mr. O on the table reports,
"The block is in front of me and close by."
At the end, Mr. O on the table reports,
"The block is off to my right and further away."

Did the block stay in the same place in this experiment?
Mr. O on the table reports,
"No, the block did not stay in the same place.
The block moved in this experiment."

At the beginning, Mr. O on the truck reports,
"The block is in front of me and close by."
At the end, Mr. O on the truck reports,
"The block is in front of me and close by."

Did the block stay in the same place in this experiment?
Mr. O on the truck reports,
"Yes, the block stayed in the same place.
The block did not move in this experiment."

Mr. O is not like a person.
Mr. O thinks he is the most important thing in the world.
Mr. O notices only the objects in the system we make up for him to observe.
He notices everything that happens with the objects in this system.



(Continued from page 198)

however, lightens the burden for the teacher because it facilitates teacher-pupil review without the necessity of repeating entire experiences; and the repetition of such words as "Mr. O" and "configuration" reinforces learning. The questions which appear in the children's manual are intended to stimulate discussion, and application of learning is enhanced by the inclusion, toward the end of the manual, of problems that are to be answered individually. The children's manual is an adjunct. The lessons can be taught without it, and the project staff suggests that many lessons omit it. The project staff is alert to the necessity of teacher adaptation of content as the situation demands. For example, one of the books makes this precautionary statement:[11]

> As we prepare this course, we fear that you will think we have some secret formula for teaching science. We do not! As we see it, our instructions will help "clue you in." You will make changes, additions, and deletions as you find necessary... You may use other activities along with these lessons. Simple examples may occur to you that fit into the lessons. Use them!

The extract (pp. 199–201) is reproduced from the children's manual for *Observing Systems*.[12] It is a review lesson in which Mr. O, a cardboard man, observes and reports the position of a block of wood on a moving truck.

Evaluation: In 1964–1965, these books were used in five California schools—four public elementary schools and one private elementary school. They were used both by classroom teachers trained by the project staff and by staff members in experimental teaching. In addition to feedback of oral evaluation and written reports, classrooms were frequently observed by staff members. The materials were subsequently rewritten as weaknesses and difficulties were exposed. Testing has been primarily of the practicum type, in which children are asked to perform specific tasks, which can be completed only if they have actually learned what was taught.

The Science Curriculum Improvement Study expects to publish a preliminary commercial version, which will be evaluated in four major national centers.

The multiple-science approach

The Elementary Science Study

A project of Educational Services Incorporated, in Watertown, Massachusetts, the Elementary Science Study is the leading exponent of the multiple-science approach. It is characterized by an almost complete lack of structure and continuity in its published materials. Its rationale is primarily to develop elementary-science activities that facilitate the flow of scientific ideas because of their *inherent interest* and meaning to children. The Elementary Science Study has avoided sequence, continuity, and restriction of published materials to particular grade levels. They have produced well planned and classroom-tested resource units that can be adapted by an elementary-science curriculum committee or director to the needs of his school or system.

"The spirit of science, the chance of discovery, the rewards of investigation" are emphasized.[13] This program's organization and philosophy of teaching science is perhaps most nearly like that which is advocated by the authors of this textbook.

More than forty units have either been extensively developed or are in some stage of evolution. Some idea of their variety may be gathered by this partial listing:

Properties of Materials
Cells as Structural Units
Animal Behavior
Characteristics of a System
A Life Cycle
Skeletal Structure of Animals
Circuits and Magnets
Classification
Rocks—Classification and Identification
Pendulums
Mixtures of Chemicals
Optics
Symmetry, Color, and Form
Marine Life
Heat and Temperature
Physical Geometry
Yeast
Chemical Reactions
Biological Environments
Soils
Solutions and Dilutions

The unit entitled *Behavior of Mealworms* exemplifies their approach. This unit is one of several designed to illustrate animal behavior. The others are "observations of goldfish in grade 1, the metamorphosis of butterflies in grade 3, the reactions of planaria to light, and the behavior of mosquito larvae."[14] The mealworm unit begins with students' observation of mealworms. Mealworms, which are easily grown, are chosen because their behavior is relatively simple and consistent. The questions that arise from these observations are investigated experimentally if at all possible. Suggested questions are "What is the most effective way to make a mealworm move backwards?" and "How do mealworms find a pile of bran, and why do they remain in it?" These problems supply an opportunity for children to observe and to experiment systematically with the behavior and structure of mealworms by simple investigation, collection of data, statistical analysis, design and construction of apparatus to test hypotheses, and controlled experimentation. By transforming the mealworm's environment, children attempt to find out how the mealworm behaves in response to these changes. In their experiments, they encounter the problem of controlling many variables. These activities have been tested with sixth-grade classes, whose teachers are encouraged to try new procedures if they wish.[15]

The extract reproduced below describes the first few days of exploratory study, the function of specific assignments, and the nature of the statistical analysis by which the problem, "How can mealworms be made to back up?" is solved.[16] Specific suggestions for making simple apparatus are accompanied by facts and information for teachers, some suggested experiments, and general rules for animal experimentation.

> ### *What Can Be Found Out about Mealworms by Watching Them?*
>
> The initial assignment for students is to have them make cursory observations of mealworm behavior. They experiment at home and answer on paper the questions: "What did you do?" and "What did you find out?" Some might be motivated by the challenge of seeing who can discover the most. For the students who are uncertain, a few ideas from other students of what they plan to do might be helpful.
>
> Mealworms are distributed "cafeteria style." Each child receives a handful of bran and five mealworms in a stapled wax-paper sandwich bag.
>
> The discussion which follows the investigation at home might begin with the question, "Who found out something which no one else did?" The experiments performed are varied and often appear illogical as seen from this sampling:
>
> 1. I put him on an ice cube and he doesn't like cold.
> 2. I placed it on its back.
> 3. I dropped vinegar on the tail and he didn't like it.
> 4. I held a pen in front of it.
> 5. I put him between piles of sugar and salt.
> 6. I bounced him around on a sheet of plastic.
> 7. I shined a flashlight on him and he crawled away.
>
> If the children wish to draw conclusions from their observations, they should be made to realize that the evidence upon which the inferences are based is quite inconclusive.
>
> These undirected activities provide a background for the more refined observations and experiments on mealworm behavior which now follow.

How Can Mealworms Be Made to Back Up?

From the previous discussion will come some mention of mealworms backing up in certain situations. These observations can be capitalized upon in this lesson with the question of what things cause the organism to react in this unusual manner. At home, the students are to try to make their mealworms move backwards by as many different methods as they can devise.

The procedures which caused the desired effect can be listed on the board the following day. The question can be raised of which way is the best for making a mealworm move backwards. "Which method would you select to force the mealworm to back up the greatest number of times?"

Guesses can be heard, but there will probably be little agreement. Now the problem is, "How can this be found out?" Students may need help to see that quantitative results obtained by counting will best answer the question.

Four or five representative techniques which elicited the backing response are selected for further study. Students perform each at home, recording on a chart the total trials and the number of times backing occurs. Class totals can be tabulated efficiently by listing the categories at separate places on the blackboard. The students all go to the board and write their figures in the appropriate column.

The summary from one class is illustrated below:

What was done	Times tried	Times not backwards	Times backwards	Rank from best to worst
Flashlight ½" away	106	58	48	3
Match ½" away	95	28	67	1
Drop of water on head	90	51	39	5
Wood stick in front	110	63	47	4
Blow on head with straw	119	60	59	2

If percentage has been studied previously by the class, it will be of practical value here.

The units are richly suggestive of ways to teach science by Inquiry. They supply helpful factual information to the teacher, and are most helpful in anticipating new or unexpected directions and student errors and misapprehensions. The wisdom gathered from classroom testing is clearly in evidence. The kinds of questions which children are likely to ask are anticipated, and suggestions by which the teacher may take advantage of these questions are plentiful. The unit is completely based on experiment and observation, which through discussion and analysis lead to valid conclusions. Children, guided by an informed teacher, carry out the experimental and observational work.

In a somewhat more fully developed form, they have prepared a self-contained teaching unit entitled *Kitchen Physics*, which investigates the properties of liquids. There is no attempt to incorporate explanatory molecular theory; it "... *does* intend to introduce [the child] to some phenomena, to let him discuss what he sees *in his own words*, and to measure what he does in familiar units. From this experience, we hope he will develop a sound basis for further study in science which may come later."[17]

The unit is designed for the sixth and seventh grades, because even though younger children can do most of the experiments they cannot handle the ideas required to explain what they see and do. The content of the unit is divided into six sections:

1. "Time to Empty" (2 to 3 lessons).[18]

While examining the flow of liquids through various sized openings, the children are introduced to the equipment and to experimental technique and error. They immediately begin making observations, making quantitative measurements, and taking data. In addition, they begin to make predictions and to perform experiments to test them.

2. "Beading of Water Columns" (4 to 5 lessons).[19]

The children continue to examine the flow of liquids, this time by taking a closer look at the liquid column as it falls from a bottle and breaks up. Once again they find out that varying either the hole size or choice of liquid or both has a measurable effect. They learn to represent their data graphically and begin to appreciate the usefulness of logically ordered arrangements.

3. "Heaping and Drops" (3 to 5 lessons).[20]

By performing some fairly simple experiments with liquids, the children begin to isolate some of the properties of liquids. In attempting to explain what they have observed, they formulate ideas about *heaviness* (density), *thickness* (viscosity), *grabbiness* or *stickiness* (surface tension and cohesion). At the same time, they devise ways of testing and finding out if their ideas are right.

4. "Balances—A Way to Measure 'Heaviness' and 'Grabbiness'" (5 to 15 lessons).[21]

The children assemble a simple equal-arm balance with materials supplied in the students' kits. With it, they measure the "heaviness" of various liquids. Then, by modifying their balances slightly, they make a tensiometer and measure the "grabbiness" of various liquids by finding out how much force (weight measured in washer units) must be added to one arm of the balance beam to make the other arm lift a plastic plate off the

> surface of the liquid. They may then perform a variety of experiments to extend these measuring techniques to the investigation of related problems."

5. "Tugs of War and the Skinlike Effect" (2 to 5 lessons).[22]

> The children see some rather fascinating events which they try to explain by applying knowledge gained in previous experiments. The tug-of-war experiments center around the attractive forces at work within a liquid and between different liquids; the skinlike-effect experiment has to do with surface tension. These activities provide the children with an opportunity to extend the experience and knowledge already gained into a study of more related phenomena.

6. "Absorption and Evaporation" (6 to 12 lessons).[23]

> The children perform several experiments involving absorption and evaporation of different liquids in different materials to reveal still another aspect of *grabbiness*—cohesive and adhesive forces at work. In the process, they become aware of the need to design experiments with only one variable (changing factor), and, by observing that opposite forces acting simultaneously tend to nullify each other, they begin to develop an understanding of the *state of equilibrium*.

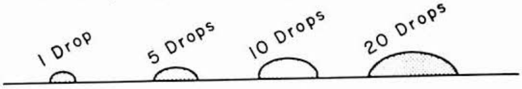
This extract from Chapter 3, "Heaping and Drops," is a procedural exemplar. Following a prediction of the comparative sizes of drops made with soapy and plain water and an experimental verification of their prediction, the following procedure is suggested:[24]

> If, after performing the experiment, some children cannot see any difference in the size of plain and soapy water drops, ask them whether they thoroughly cleaned their droppers between experiments. (This is the most common cause of variation in results.) If they still are not convinced, ask them to try counting the number of drops it takes for each liquid to reach the 10 ml mark on their cups. Or else they could try putting 100 drops of plain water into one cup and 100 drops of soapy water into another and then compare the level reached by each.
>
> Another interesting activity which helps give the children a feeling for the *grabbiness* of water is to have them place a few drops of plain water on waxed paper. These drops will very nearly approximate hemispheres as long as the drops are small. Ask them to place or push their drops very close together. They will see them almost leap together to form a single

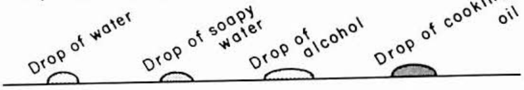
> See *Background Information* for an explanation of what the children might mean by *grabbiness*.

drop. However, when the experiment is repeated with soapy water or alcohol, they will find the liquids do not heap or leap as well as the plain water drops did. They might also like to place drops of various liquids on different surfaces. The results of some things they might try are shown in the accompanying figure.

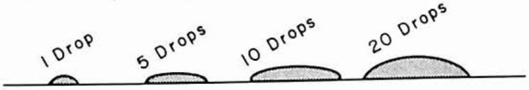
Water Drops on Waxed Paper



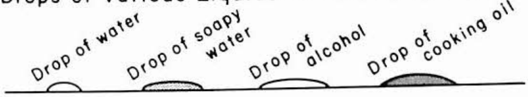
Drops of Various Liquids on Waxed Paper



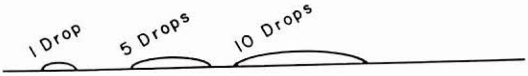
Water Drops on Aluminum Foil



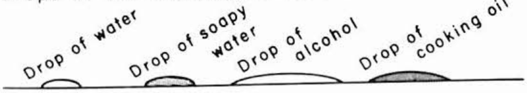
Drops of Various Liquids on Aluminum Foil



Water Drops on Glass



Drops of Various Liquids on Glass



Complete the activities on heaping and drops with a discussion of what the children think happened. In attempting to explain heaping, children generally formulate "theories" like the following:

> "The heavier it is, the more it gets pushed down; therefore, oil, alcohol, and soapy water must be heavier than plain water."
>
> "Soapy water can't heap as high as plain water because gravity pulls it down more."

By *heaviness*, the children usually mean *density*. That is, given the same volumes of water, alcohol, soapy water, and oil, they believe the water will be the lightest. This distinction can be cleared up later. Here it is best to concentrate on getting ideas.

> "The thicker it is, the less likely it is to run over the edge. Therefore, water is thicker than soapy water, oil, and alcohol."

The children generally mean *viscosity* when they say *thickness*. Viscous liquids are those which do not flow freely, like molasses or honey, to pick an extreme.

> "Water holds together better than soapy water, oil, or alcohol; it's grabbier."
>
> "Water heaps higher than the other liquids because it isn't as loose."
>
> "It pulls together better, so more of it can stay above the level of the cup."
>
> "Gravity can't pull the drops of water out of shape as easily as it can the other liquids because they aren't as sticky."

The thickness "theory" presents an interesting lead into a discussion of a subject they studied earlier. The data they collected in Chapter 1, "Time to Empty," indicated that oil is thicker than water. Yet in this case they find that water heaps higher than oil!

If the advocates of the thickness "theory" are still unwilling to admit that their explanation is not completely satisfactory, let them try some more experiments. At a similar point in one of our test classes, the students filled one tube with water and another with oil. After sealing the tubes, they inverted them and timed how long it took a bubble in each one to rise to the top.

Another experiment to measure thickness might involve timing how long it takes two small jars—one half filled with a thin liquid and the other half filled with a thick liquid—to roll down an incline.

Perhaps your children can think of other experiments which would enable them to test their ideas. When they begin to think of ways of testing heaviness, they will surely lead themselves into the next chapter: "Balances—A Way to Measure 'Heaviness' and 'Grabbiness.'"

BACKGROUND INFORMATION

Heaping. In the heaping experiment there is a point at which just one more drop will cause the liquid to spill over. This point depends on the density of the liquid (called *heaviness* by the children), its viscosity *(thickness)*, and the surface tension (*stickiness* or *grabbiness*). These last two properties tend to restrain or retard overflowing. The density and viscosity of plain water and soapy water are similar, but the surface tension of plain water is much greater. Plain water, because "it holds together" better, is able to restrain a greater weight from overflowing than other "weaker" liquids such as alcohol or oil.

The greater surface tension of water is due to the fact that the attractive forces between water molecules are stronger than those between molecules of alcohol or oil. In the case of soapy water, the soap molecules get in between the water molecules and reduce the normally strong forces holding them together.

Drops on Waxed Paper. If you experimented with drops of water on waxed paper, you probably noticed that the drops, if small, were almost hemispheres. This indicates that water holds together very well and is not strongly attracted to the wax. When the children pushed the drops together, they saw how the drops almost seemed to leap together to form a single drop.

If you used soapy water too, the results agreed with earlier experiments: soapy water drops *did not* heap or leap as well. This is partially because the soapy water wets (is not repelled by) the wax surface, while plain water does not; that is, with soapy water we contend not only with intermolecular (cohesive) forces which produce "grabbiness," but also with the attractive (adhesive) forces between two substances (in this case the wax and the soapy water). These external "sticky" *(adhesive)* forces between two substances (which are small between plain water and wax) acting against the internal "grabby" *(cohesive)* forces in a substance, reduce its apparent "grabbiness." Therefore the experimental results, while in agreement with what would be expected, are not due solely to the smaller attractive forces in soapy water.

Evaluation: During the 1964–1965 school year, 250 teachers used the five units and apparatus kits which have been commercially prepared as a "Sampler." They were used in elementary schools in Maryland, Colorado, California, Massachusetts, New York City, and Connecticut.

These teachers periodically report on their progress, and are visited by staff members for purposes of evaluation. There has been no objective testing, because the Elementary Science Study has taken the position that the testing instruments currently available are not valid measures of its objectives.

Science – a process approach

Three important curriculum projects are directed at preparing complete elementary-science curricula. The project which has moved ahead most rapidly is sponsored by the Commission on Science Education of the American Association for the Advancement of Science, which, in 1965, published fourteen volumes of its third experimental edition of *Science – A Process Approach.* The orientation of the American Association for the Advancement of Science program is clearly stated in its *Teacher's Guide:*[25]

> There is joy in the search for knowledge; there is excitement in seeing, however partially, into the workings of the physical and biological world; there is intellectual power to be gained in learning the scientist's approach to the solution of human problems. The first task and central purpose of science education is to awaken in the child, whether or not he will become a professional scientist, a sense of the joy, the excitement, and the intellectual power of science. Education in science, like education in letters and the arts, will enlarge the child's appreciation of his world; it will also lead him to a better understanding of the range and limits of man's control over nature.

The process skills listed below form the framework on which the curriculum is organized:

1. Observing.
2. Recognizing and Using Number Relations.
3. Measuring.
4. Recognizing and Using Space/Time Relations.
5. Classifying.
6. Communicating.
7. Inferring.
8. Predicting.

In acquiring and practicing these skills, children are confronted with many different kinds of science experiences. Content is the raw material out of which skills emerge. Learning facts and principles of the sciences is *not* the goal, although it is confidently expected that by the time the child finishes the third grade he will know many important science concepts and have at his command some "organized knowledge" about his scientific environment.[26]

Throughout the intermediate grades, the manuals enlarge on the process skills by means of exercises, which become progressively more complex and more nearly like scientific research. The emphasis shifts to such higher skills as hypothesizing, defining operationally, manipulating variables and their controls, formulating mental models, and interpreting data.

Each exercise is focused on a single process skill, which, by virtue of the spiral curricular design, is recycled and amplified. For instance, the kindergarten and first-grade volume, which is numbered 1A, begins with an exercise on "observing" and continues with five more "observing" lessons. The kinds of skills and their frequency are given below:[27]

Skill	*Content*
Observing 1	Perception of Color
Using Space/Time Relations 1	Recognizing and Using Shapes
Observing 2	Observing Temperature
Observing 3	Sets and Their Members
Observing 4	Observing Color, Shape, Texture, and Size to Identify Sets and Their Members
Classifying 1	Classification Using Leaves or Nuts
Using Space/Time Relations 2	Recognizing Direction
Using Space/Time Relations 3	Spacing Arrangements
Classifying 2	A Purpose of Classification
Using Numbers 1	Order Properties
Observing 5	Perception of Sound
Observing 6	Perception of Odor
Using Space/Time Relations 4	Shapes and Their Components

By the sixth grade, the kinds of process skills and their relative complexity have been drastically changed:[28]

Skill	*Content*
Defining Operationally 7	Temperature and Heat
Experimenting 5	Heat and Work
Defining Operationally 8	Density
Formulating Models 8	Life Cycles
Interpreting Data 14	Growing Plants in Various Colors of Light
Experimenting 6	Chromatography
Interpreting Data 15	Human Characteristics
Experimenting 7	Photosynthesis
Controlling Variables 13	Fermentation
Experimenting 8	Growing Crystals
Interpreting Data 17	Moon Photos
Formulating Models 9	Examining the Light-Curve of a Variable Star

At the end of six years, the child will have passed through seven exercises in operational definition, fourteen in interpreting data, eight in experimenting, thirteen in controlling variables. These exercises are not completely restricted to the objective named. For example, many which have different titles are experimental and require operational definition.

The style and organization is illustrated by these two extracts from representative volumes:[29]

Observing 9: OBSERVING SOLIDS CHANGING TO LIQUIDS

Objectives

At the end of this exercise the children should be able to:

1. identify the changes which occur when a solid changes to a liquid, including changes such as height, width, color, temperature, and shape.
2. identify the changes which occur when a liquid changes to a solid, including changes such as temperature, color, and shape.

Rationale

In addition to observing and describing likenesses and differences between objects it is important to be able to compare and describe the changes which take place when objects melt or solidify. This process is applied in a practical way as a means of identifying crystalline solids on the basis of their melting points.

The children may have trouble with the words liquid and solid (often confused with salad) and no special attempt is made to define them. The activities can be presented without using these words if the children do not seem ready for this vocabulary.

Vocabulary

Melt, melting, hotter, faster, slower (solid, solidify, liquid, liquefy).

Materials

One small ice cube and one cube of ice about 3 inches in each dimension, made by freezing water in a 1-quart paper milk carton
An insulated bucket for ice
Candle (one that will drip) or birthday candles
Lard or vegetable shortening
Cork, marble, wax (a colored wax is preferred), about 15 grams (½ oz.). Wood's Metal. (This is a low-melting-point alloy, available from scientific supply companies.)
Four custard cups
A hot plate and a pot for boiling water
Tongs or pot holders
Towel

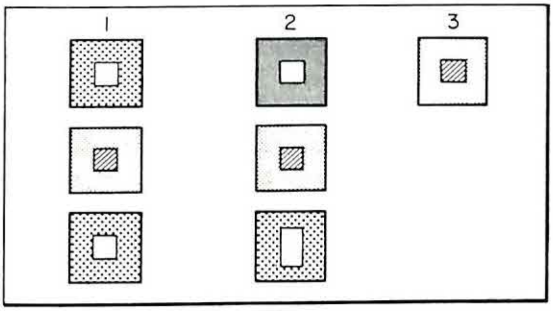
For each group of four or five children:
One cube of ice
One paper towel

One large white saucer. The saucer may be heated by immersion in *hot* water for several minutes. Be sure it is dry before it is used.

One cube of modeling clay, one of ice, two cubes of butter at room temperature, one cube of butter just removed from a refrigerator—about 40° F; (5° C).

A chart like the one shown below, large enough for the whole class to see. The top row is for Activity 1, the middle and bottom rows for Activities 2 and 4, respectively. This could be three separate charts, one for each activity, or one chart as the teacher prefers.

Squares of colored paper to represent the materials used: three yellow for butter, one gray for clay, two white for ice. All of these squares should be the same size. In addition, one large white square to represent the 3-inch ice cube. Picture or sketch a refrigerator to put in one of the squares along with a yellow square.



Originating the Problem

Interest could be aroused as a result of a snowstorm, the spring thaw, finding some ice on the playground, using butter at lunch time, or eating a popsicle. Some leading questions might be:

Does ice cream have a shape when it is put in the cone?

What about a popsicle? Is it a solid as it comes from the freezer?

Does the ice cream change its shape as it melts?

What is it about the tongue that causes the ice cream to melt? (It is hotter than the ice cream.)

Can ice cream drip?

Why does ice cream melt faster at one time than another? (The air may be hotter.)

Give each group (four or five) an ice cube on a paper towel. Ask one of the children what will happen to the ice. Will the ice change? How does he know it will change? Give each child in the group an opportunity to hold the ice cube in his hand. He will see the liquid on his hand as well as on the remaining ice.

Instructional Procedure

Activity 1

Place equal-sized cubes of modeling clay, butter at room temperature, and ice on a large, hot saucer before the group of children. Ask the children to identify the objects as to material, shape, and size (show by fingers). Are they all the same size, color, odor, shape?

As they are describing the cubes, some cubes will begin to melt. Let the children discover it. Do they notice which one melts first? What happens when it melts? Does the color change on melting? Describe the differences, if any. What is happening to the cube of clay? Is it changing? Will the clay cube ever melt?

Ask the children to order the cubes in sequence according to the time melting started (first, second...) and to the rate of melting (fastest, slowest, and so on). Their observations may be recorded by having the children fill in the first line of the squares of the chart prepared for the bulletin board or drawn on the chalkboard. Have them put the colored square to represent the cube that first melts completely under number one, and so on. The sequence may be (1) ice, (2) butter, and (3) clay (does not melt), although it is not easy to predict the order which may depend on the particular conditions.

Activity 2

Place on a warm saucer in front of the children two cubes of butter, both the same size but one close to room temperature and the other freshly removed from the refrigerator. Encourage them to describe what they see. Have them touch the two cubes lightly. Does one feel cooler than the other? Ask the children to guess which cube will become liquid first. Do not tell them; let them find out for themselves. As the cubes melt, have the children describe the changes as in Activity 1. Fill in the second line of the chart, using the yellow squares. Use the picture of a refrigerator on the square to designate the cold cube of butter. How many of the children predicted correctly which cube would melt first? Ask if the butter is different after melting.

The melted butter may solidify again as the saucer cools. If this happens, let the children discover it and describe this change. A child may ask why this happened, or why the warm butter melted faster than the cold butter, or why the ice melted faster than something else. Although the objective of this experiment is to elicit description, use persistent questioning to bring out the idea that things melt when they get warm enough and solidify when they get cold enough.

Activity 3

Light a candle and let the children observe the melting wax drip on a cool surface and change back to a wax again. This activity can be extended by letting the children handle a candle as well as the drippings after they have cooled.

Activity 4

Show the children the large and small cubes of ice. Ask them to tell you what will happen to the cubes when they are placed on the saucer in the room. Ask which will melt first. Have them place symbols for their prediction on the third line of the sheet. Ask questions such as:

What shape is the solid ice now?
What will happen to the cubes if they remain in the room?
Will both of them melt?

Will they become solid or liquid?
What shape will the ice be after it has melted?
What is in the room that causes ice to melt? (Warm air.)

Have the children show, by moving their fingers, how the size of the cubes will change as they melt. After they discuss what they think will happen, allow the two cubes to melt so they can check their predictions.

Appraisal

Place a tablespoonful of lard or vegetable shortening in a clear Pyrex dish. Ask the children what they think would happen to the lard or vegetable shortening if it were heated on a hot plate. They should predict that it would melt and change shape as the liquid forms. They should describe what would happen in terms of changes in height, width, color, temperature, and shape.

Ask the children what they think would happen to melted lard or solid vegetable shortening if the dish were taken off the hot plate. They should predict that it would change back to solid lard or shortening. They should describe what would happen in terms of color, temperature, and shape.

Controlling Variables 5: THERMAL EXPANSION

Objectives

Following this exercise the children should be able to:

1. identify variables which may affect the expansion of a given material when it is heated.
2. demonstrate how variables may be manipulated and controlled.
3. state and demonstrate that not all materials expand at the same rate when they are heated.

Rationale

In the preceding exercise the children controlled variables as they determined that different materials conduct heat at different rates. In this exercise they will gain additional experience identifying, manipulating, and controlling variables as they compare the rates of expansion of substances when they are heated.

Most substances expand when they are heated and contract when they are cooled. There are exceptions to this, the most familiar being the expansion of water as it changes from liquid water to ice. Thermal expansion is an important property of matter and must be considered in construction work. Bridges, roads, and pipelines, for example, are provided with expansion joints.

Vocabulary

Expansion, expand, contraction, contract.

Materials

Candles (one for each member of the class)
Expansion apparatus with metal rods—aluminum, brass, copper, steel (last two optional)—see Activity 3

Two flasks (either erlenmeyer or florence) 150 ml or larger
Two one-hole rubber stoppers
Two glass or plastic tubes 15 or 20 cm long to fit rubber stoppers
Adhesive scale tape (millimeter)
Bowl or 1-liter beaker
Stop watch
Dry cell, electric light, and metal rod to serve as a switch (thermostat) as shown in the photographs in the Generalizing Experience (optional)

Originating the Problem

Arrange on a table two flasks, each with a one-hole rubber stopper and a glass tube through the hole, several metal rods, and several candles. One of the flasks should be filled with water. Say to the children that you have a collection of things that you would like to have them ask questions about. Tell them that their questions should be ones that can be answered only with a *Yes* or *No*. Their questions may be as follows:

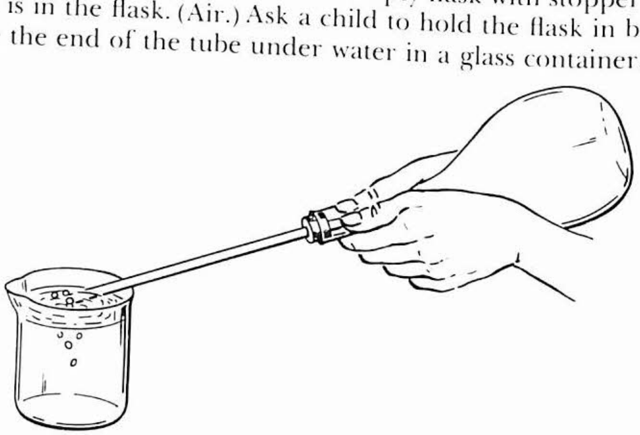
Is that water in that flask?	*Yes*
Does the other flask have air in it?	*Yes*
Will we heat those rods?	*Yes*
Are those rods the same ones used in our last exercise?	*No*
Are those rods of the same metal as the last rods we used?	*Yes*
Is the rod in the stand aluminum?	*?*

When the questions have been exhausted, or ten have been asked, suggest that the children summarize what they now know about the equipment on the table.

Instructional Procedure

Activity 1

Call the attention of the class to the empty flask with stopper and tube. Ask what is in the flask. (Air.) Ask a child to hold the flask in both hands and place the end of the tube under water in a glass container.

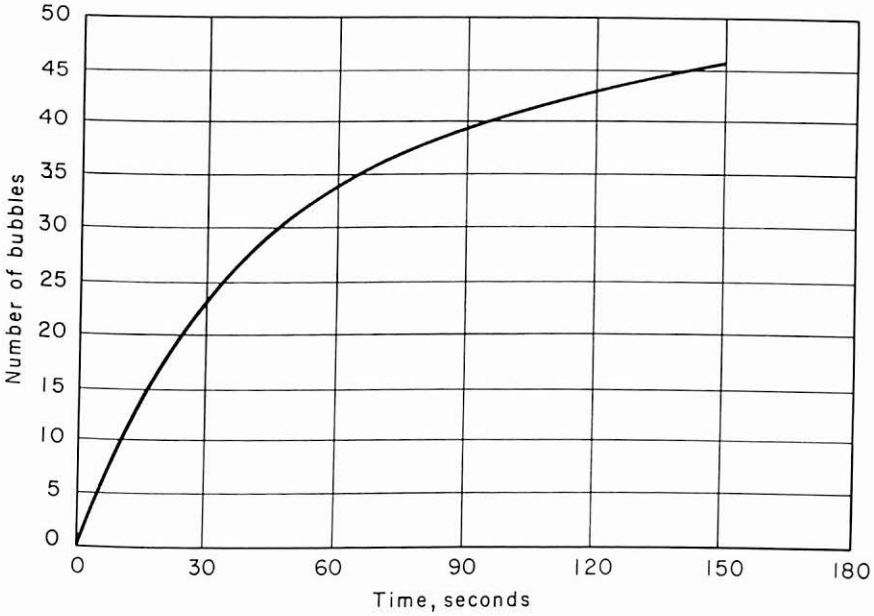


Ask the children to count the number of bubbles that escape from the end of the tube and to record the number every 30 seconds until there are no more bubbles escaping. More bubbles may be obtained if the flask has been in a refrigerator or other cold area before the class session. The data may be recorded on a table as shown on the following page:

AIR EXPANSION

Time	Total Number of Bubbles	Difference in Number
30 Sec.	23 Bubbles	23
60 Sec.	34 Bubbles	11
90 Sec.	39 Bubbles	5
120 Sec.	43 Bubbles	4
150 Sec.	46 Bubbles	3
180 Sec.	47 Bubbles	1

Ask the children to plot the data on a graph. The time in seconds should be on the x axis (horizontal) and the number of bubbles on the y axis (vertical).



Ask the children for an explanation of the bubbles. The explanation may come quickly. (The hands warmed the air in the flask and it expanded.) If there is any doubt in the minds of the children, the experiment should be repeated. If several flasks are available, groups of children may carry on the experiment. Ask the children to identify the variables in this experiment. (The temperature of the air in the flask at the beginning of the experiment and the temperature of the children's hands.) Ask how these variables can be controlled. (Start with flasks of known temperatures and ask the same person to hold the flask.)

At present, all text material is written for the teacher, who, as is demonstrated by these extracts, is assisted by the suggested procedures for beginning experiments and for carrying them through. No supplementary readings for children are suggested, although trade books and supplementary references will enrich the daily routine. Children are required to *do* something in each exercise, because a physical action or an experimental procedure is incorporated. Reading as a source of scientific knowledge is ignored. Children learn science by action, by direct contact with phenomena.

Each exercise is preceded by a listing of specific objectives that are to be achieved. The AAAS has surpassed the other programs because it has delineated practical behavioral objectives by which teachers can assess outcomes. The formulation of the objectives was undoubtedly the most difficult task which the writing groups faced. By this achievement, they have been able to avoid such verbalizations as "development of appreciations or understanding," and have managed to minimize facts as a functional outcome. This approach in science curriculum construction is novel and has been long sought by specialists in evaluation.

For example, in the exercise "Observing 22," ("Observing Some Animal Responses to Stimuli"), these two objectives are listed:[30]

> At the end of this exercise the children should be able to:
> 1. identify stimuli in an environment.
> 2. identify the corresponding responses to identified stimuli.

In this exercise, children study the responses of goldfish and turtles to various kinds of stimuli. At the end of the exercise, children apply in a "Generalizing Experience" their knowledge of stimuli and responses to other animals. In the "Appraisal" section, children observe and report on such animals as snails, parakeets, and frogs. The manual suggests that the teacher discuss their observations, asking them how they can learn more about these animals. The class is organized into small groups, which present stimuli, observe, and record responses, activities which are followed by discussion and, if necessary, by repetition of the experiments. In this appraisal and in the generalizing experience, teachers informally evaluate how well children identify environmental stimuli and correlate animal responses with these stimuli.

In addition to behavioral objectives, each exercise presents a fully developed "Rationale," which describes the function of the exercise as a part of the total scheme, lists the concepts, and tells why they are important. The "Rationale" section establishes the intent of the exercise and its "instructional style." The relative stresses accorded the different process skills are discussed, and supplemental factual information is usually provided.

Evaluation: The AAAS program was taught by 230 teachers in 75 elementary schools throughout the nation in 1964-1965. Each teacher submitted a report, after each exercise was completed, on the problems which he and the children encountered, and added his suggestions for change. He also rated three children on a "checklist of competencies" at the end of each exercise, a rating which was supplemented by additional staff testing. A new instrument for assessing mastery of process skills, the "Science Process Test," is also being tested experimentally. It is to be given annually and administered individually. (See Chapter 11, pp. 386–387.) The results will provide a profile of children's progress in each of the process skills. Several other evaluative instruments for measuring the ebb and flow of interest in science have been devised to aid the teacher in assessing curricular outcomes.

The Elementary School Science Project (The Utah State University Project)

The Elementary School Science Project is limited to the primary grades. Its major purpose is to select from the various sciences those phenomena which will strengthen capacity to observe and to abstract whatever is pertinent from observation. The claim is advanced that 90 percent of the activities "serve to help a pupil perceive more fully whatever he is exposed [to]. He is led to see not only the object before him, but also its shape with an awareness of its comparative size, its color, relative position, quantity, possible interaction with other objects, strength of its interaction, etc."[31] In addition to gaining practice in observation and perception, accompanied by growth in understanding the important concepts, ideas, and interrelationships which comprise the structure of science, children are expected to become better able to analyze, classify, and record information meaningfully.

Some of the project's content is unique. For instance, three quarters of the manual *Science for First Grade* is given over to puzzle solving, in which children practice classifying, identifying similar concepts, generating sets, and pairing; they gather the necessary data for these actions by observation and manipulation.

Some of the content, notably that which is in the *Biological Supplement*, is much more traditionally oriented than the rest and appears similar in content and structure to conventional elementary-science textbook series, even though their objectives are different.

The manual *Science for First Grade* contains four major units:[32]

I. Solving Puzzles.
    Observing
II. Solving Puzzles.
    Seeing
    Hearing
    Touching
    Smelling
    Tasting

III. Changes.
    Observing
    Measuring
    Measuring changes
IV. Systems and Interactions.

The Elementary School Science Project has estimated that most first-grade children will be able to complete this curriculum if it is taught for one hour per day, two days a week, for the school year. If the *Biological Supplement* is added, much more time is necessary.

The *Biological Supplement* contains four major units, of which two are process-centered and two are traditional:[33]

I. Observing.
II. Classification.
III. Growing Plants.
IV. Microscopic Life.

Typical extracts of content and procedure are given below. The first extract is from *Science for First Grade,* and is taken from the unit on "Hearing as a Way of Gaining Information to Solve Puzzles." In addition to the objective and the materials and methods, the teacher is given an explanation of the concepts, some illustrations, and a trade-book reference to read to the children. In addition, there is a discussion of the activities suggested for the classroom.[34]

The second extract is from Unit III, "Observing Changes." Only the first three of the thirteen activities in this subsection are reproduced:[35]

The manual lists some sixty children's trade books which are suitable for supplementary reading to the class, as well as five charts and twenty films and filmstrips which will enrich instruction.

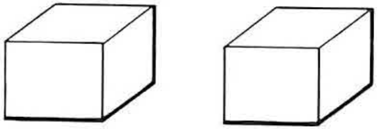
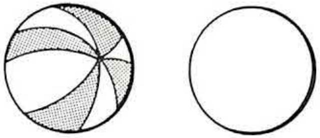
To give some of the flavor of the *Biological Supplement,* these extracts are provided from Unit I, on "Observing," and from Unit III, "Growing Plants":[36]

Method: A statement of objectives and sub-objectives is given for each activity. Materials are listed, and apparatus and techniques are illustrated with simple diagrams. Instructions and suggestions to the teacher guide children in planning, acting, and evaluating. The blind alleys and errors which children may encounter are often specified. Pedagogical emphasis is on discovery, *not* on telling. Children, with teacher guidance, must find out for themselves. Much of the direct contact with phenomena is through teacher demonstrations, although there is an effort to allow children to participate directly in as many exercises as possible.

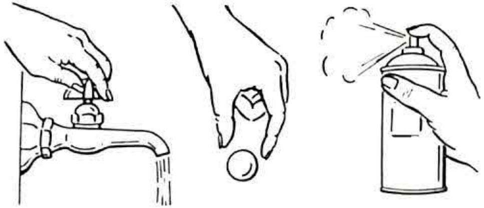
Evaluation: In 1964–1965, sixteen teachers in the state of Utah used the complete first-grade program. These teachers reported on their

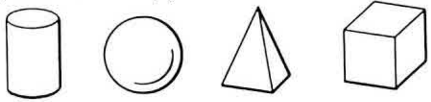
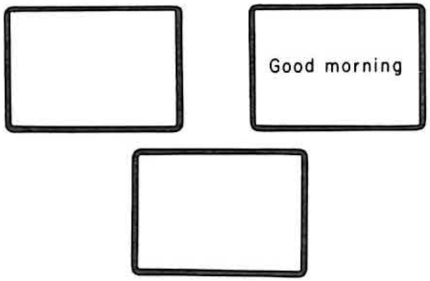
(Continued on page 229)

UNIT II
HEARING

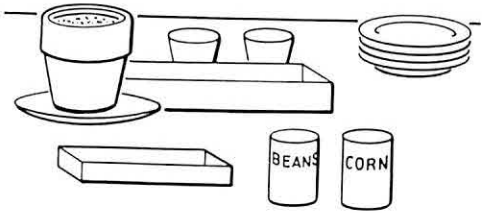
Objectives	Materials and Methods	Explanations and Illustrations
To get a little closer to "how much heavier or lighter."	Materials: Two boxes same size—one weighted 5. Compare heavy and light. Have one child test by feeling (eyes shut) the weight in one hand and a different weight in another hand, or at different times. The rest of the class observe by seeing.	 Two boxes of same size, but weighted differently. A steel ball and a styrofoam ball. Note that the child changed the position of his hands because of the weight.
	Materials: Oranges, grapefruit, and balls of equal size. 6. Use oranges and grapefruit with balls the same size to give the conception of difference in weights of objects the same circumference.	 Refer to Unit II Reference Books, no. 17.

UNIT III
OBSERVING CHANGES

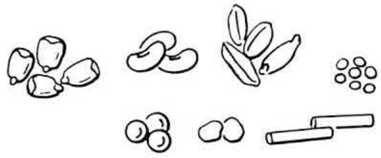
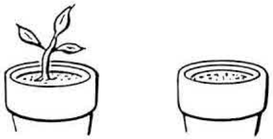
Objectives	Materials and Methods	Explanations and Illustrations
To emphasize *change* in conditions. To note the *change* is an important part in observing.	Materials: None 1. Turn on water in sink. (What change has taken place? How do you know it took place?) Drop an object. (What object was dropped? What change?) Roll an object down hill. Turn on light, blow a whistle, spray deodorizer in room. (What changes took place?)	In each instance, ask the question, what change took place, how did they know it took place, what method of observation did they use to note the change? Did they touch it, see it, hear it, taste it, smell it? Or did they use a combination of two or more methods? 
To show that many means of observation can be used to detect change. In fact, change can be observed by same methods as identification.	Materials: None 2. Draw card on rough surface vs. smooth surface. (Also change speed of rubbing surface to see if children can detect change of sound with change of speed.)	Speed of action causes noticeable changes. Use styrofoam ball and ping pong ball as an example of rough and smooth surfaces.

Objectives	Materials and Methods	Explanations and Illustrations
	Materials: Heavy and light objects.	Steel and Styrofoam balls
	3. Lift heavy and light objects in hands. (What happens to the hands when different weights are placed on them? Is there a change? What is it?)	The hand holding the heavy weight went down.
	Blindfold child. Place shapes in his hands and ask him to tell when a different shape is placed in his hand.	Cylinder, ball, pyramid, blocks. 
	How did he tell the difference?	He could feel the difference.
	Write something on the chalkboard. Erase it. (What changes took place?)	Changed from a clean board to writing on it, then back to a clean board. 
	Move some obvious object in the room to a different place. What change?	
	Have a child stand up, move around his desk, sit down. What series of changes took place?	

BIOLOGICAL UNIT III
GROWING PLANTS

Objectives	Materials and Methods	Explanations and Illustrations
To show interaction between minerals in the soil and plants.	Materials: Pots, trays, and dishes for use in planting, germinating and growing seeds. Bean and corn seeds. Other seeds may be used instead if they are more readily available.	
	3. Plant 10 corn and 10 bean seeds in warm, moist soil and water as needed. Plant 10 corn and 10 bean seeds on a piece of moist paper towel and keep the paper moist at all times. Add no food.	Usually all of the seeds will germinate and start to grow. Stored food within the seed is the primary source of food for the germinating seed. As this stored food is used, the rate of growth of the seeds which have water only will slow down. The seeds in the soil will continue to grow as they obtain part of what they need from the soil.
	Observe every few days for about two weeks to see which seeds grow the best.	

BIOLOGICAL UNIT I
OBSERVING

Objectives	Materials and Methods	Explanations and Illustrations
To demonstrate that one of the characteristics of living things is that they grow, whereas non-living things do not. Growth is defined as an increase in the number of cells, size of cells, or both.	Materials: Corn, wheat, and bean seeds Trays of soil or other suitable growth media Some marbles, buckshot, chalk, and small rocks 4. Plant the seeds, the marbles, the buckshot, the chalk and the small rocks in different rows. Observe from time to time to see what grows and what doesn't.	 If this experiment works as it should, the seeds will grow, i.e. living things (seeds) grow, non-living substances (the others) don't. 
To help children become more aware of the many ways in which they are alike or different from other living things.	Materials: None 5. In what ways are children like adults and in what ways are they different? In what ways are children like young animals, such as puppies or kittens, and in what ways are they different? In what ways are children like young insects, such as grasshoppers, and in what ways are they different?	Begin with things that the children know and then motivate them to reason out additional, simple relationships. Consider each of the following: Size, shape, weight, height and appearance. The need for shelter, clothing, food, water and air. The need for love, friendship, work, play and rest.

Prepare chart as shown and fill in blanks as suggested during discussion. Put this chart on the blackboard and then, based on the answers given by the students, fill in the squares with a "yes" or a "no" as appropriate.

	A Child	A Puppy	A Kitten	A Young Grasshopper
Needs a place to live				
Wears clothing				
Does not wear clothing, but has fur, etc.				
Needs air				
Needs water				
Needs food				
Needs friends				
Likes to play				
Gets angry				
Grows				

(Continued from page 222)

success and the problems which they discovered. The project's sponsors have prepared a test of the skills which are necessary for concept information: (1) deliberate attention, (2) logical memory, (3) abstraction, and (4) the ability to compare and differentiate. The test consists of questions that attempt to assess the ability of first-grade children to use these skills.[37] There are fifty questions on each of the four concept formation prerequisites, and ten "designed to measure the ability to form concepts."[38] (See Chapter 11, pp. 382–385.)

Minnesota Mathematics and Science Teaching Project (MINNEMAST)

This project seeks to prepare a coordinated science and mathematics program extending from kindergarten to ninth grade. Its rationale is that mathematical skills enhance the child's ability to understand his physical and biological environment, and, conversely, that mathematical concepts arise out of scientific investigation.

The MINNEMAST program also stresses scientific operations, which are defined as:[39]

1. Observation.
2. Measurement.
3. Experimentation and experimental design.
4. Description.
5. Generalization.
6. Deduction.

Science is to be taught by applying the work processes of science—what scientists do, how they think, their modes of approach to problems. The experiences are written to provide children with the tools with which to seek and to find information and to build relationships and understanding. The children are expected to "become scientists in viewpoint and attack each learning task in science armed with the elements of process useable by the child and pertinent to the problem."[40] Content has been selected from all the scientific fields, not because facts and principles are essential in any way, but because they are the raw material on which to practice the fundamental operations of scientists.

This curriculum, like that of the AAAS, is constructed as a spiral. Each of the operations is included in the K–2 cycle; there is a second loop in grades 3–4, and a third in grades 5–6. In each loop, children experience each of the operations, so that succeeding loops generate more meaningful, more sophisticated, and better reinforced behavior. The operations are given equal emphasis in each loop. Loop 1 stresses observation and description; loops 2 and 3 shift to experimentation and deduction.

The approach is quite sophisticated. For example, the writing teams are not content just to train children to be critical observers or to give an accurate report of what they observe. The kindergarten unit "Objects" narrows the child's attention to simple objects, taken one at a time, so that he can concentrate on sensing and describing their properties. This approach begins with "Objects" and becomes progressively more intense in the first-grade unit "Objects and Their Properties."

Twelve units have been prepared for classroom trial, four for kindergarten and eight for the first grade. The four kindergarten units are:[41]

1. "Watching and Wondering" (9 lessons). A series of experiences in which careful observation and questions are encouraged and tentative answers discussed.
2. "Objects" (6 lessons). An initial exposure to objects as characterized by their properties, and to classification and sets.
3. "Our Senses" (7 lessons). Ways of increasing precision and objectivity of observation.
4. "Shape and Symmetry" (8 lessons). Early experience with such abstractions as "spherical," "triangular," and "symmetry," and testing for three forms of symmetry.

Two typical first-grade units are:

1. "Objects and Their Properties" (7 lessons).[42]

An extension of the earlier units "Objects" and "Our Senses," with a more intensive study of the meaning of properties and of classification by means of properties.

2. "Changing and Unchanging Properties" (10 lessons).[43]

Introduction to the idea that some properties of objects are changeable whereas others are conserved. The notion of control is introduced.

Their general style is well illustrated by Lesson 4 in "Objects and Their Properties," which is partially reproduced. The objective, as stated in the "Teacher Commentary," is "the operation of making a binary comparison" between the liquids taken in pairs, not learning about viscosity itself.[44]

Lesson 4: VISCOSITY OF LIQUIDS

Teacher Commentary

In the child's previous work in science, he has dealt with many properties of objects. Inanimate objects have been described by their size, shape, color, surface characteristics, and other properties. Animals have these properties, and certain behavioral traits as well. Ants have a complex society that gives them additional properties not found in many other animals. In this lesson, only one single property will be examined—the viscosity of fluids.

Whenever two objects move over one another there is a force opposing the motion. This force exists when for example, a liquid flows over some solid surface. In addition, various layers in a fluid often move at different speeds. These internal forces are molecular in origin and give rise to the property we call viscosity. Both gases and liquids flow readily, and are therefore called fluids. All ordinary fluids are viscous to some degree. In addition, many substances ordinarily thought of as solids (asphalt and glass for example) also flow at various rates. This kind of information, however, is *not* intended for the children. What they learn they wi!l discover for themselves.

This lesson helps to provide a foundation for the extremely important operation of measurement. Measurement as such is treated in a later unit and continued with emphasis in years to follow. *All* measurement is essentially a process of comparing two things. The length of a worm, for example, can be compared to a ruler; the length of a recess period can be compared to a clock; one child's arm muscles can be compared to another. Moreover, the comparison is always *binary*. Such two-at-a-time comparisons of properties occur in science time and time again.

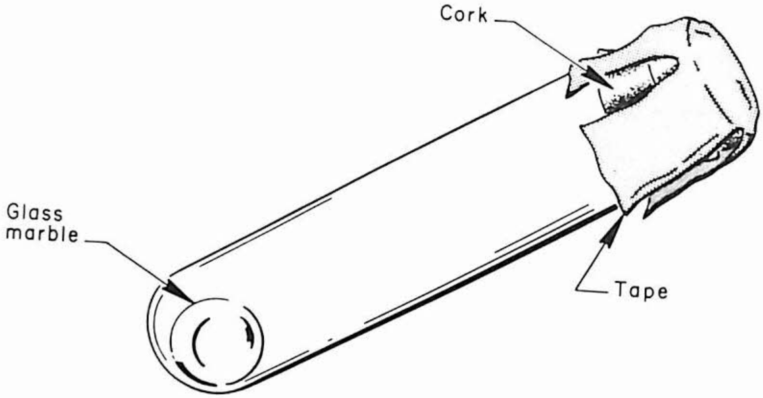
Comparing two properties may or may not yield a numerical result. In this and the lesson to follow only a relative *ordering* of a property is obtained. Thus, liquid A is more viscous than B, B is more viscous than A, or A is equally as viscous as B. This direct act of comparing a property of two and only two objects is the fundamental kind of operation which forms the heart of measurement. Viscosity, while interesting enough in itself, is not the primary topic of this lesson. The viscosity of liquids serves only to provide a suitable context for introducing the operation of making a binary comparison.

Procedure

Assemble the following equipment needed for this lesson:

1 pint tap water
1 pint clear syrup (thin the syrup, 1 part water to 4 parts syrup)
1 pint vegetable oil
1 pint motor oil (lowest price SAE 30, with no additives)
4 small jars (baby food size)
4 large test tubes for *each* group of 4 children
4 stoppers or screw caps for each set of test tubes
4 glass marbles for the test tubes of each set, the marbles of a size that will roll freely inside the tubes
12 glass marbles to be dropped in the jars of fluid
4 plastic spoons, one for each jar

A glance at the four fluids to be used indicates that clean-up arrangements will be needed. A pail of detergent solution and a towel should suffice in any kind of accident. Cafeteria trays can do much to minimize spillage problems. The test tubes should be filled with the four liquids, one liquid per tube in each set of four, and a marble inserted in each tube. Remove as much residual air from each tube as possible before stoppering or capping tightly. Although screw caps are better, stoppers may be used, as shown below.



Similarly, one set of four small open jars should also be filled, each to the same level, and a plastic spoon inserted in each. The jars are used in the first activity described below, while the closed test tubes with their marbles are used in the second activity.

Label each jar and test tube with the following symbols:

Water: ▭

Motor oil: △

Vegetable oil: ○

Corn syrup: □

Activity 1. Place the four jars containing different fluids on a table or desk in front of the class. Do *not* tell the children what the jars contain. They are to be identified only by symbol. Let some children experiment with the filled jars. They may be instructed that each of the four objects in the jars *flows*, and is therefore called a *fluid*. The children might then be asked if they know of other objects which flow.

Encourage the children to include in their descriptions similarities and differences among the four fluid objects. The children may suggest color differences and similarities (two fluids are clear and two are colored). Suggest to the children that there are other differences that will interest them.

Now encourage the children to devise their own ways of observing the objects to discover other similarities and differences. Do the objects possess any properties that have not been described before? Volunteers are called forward to try their ideas. The spoons should provide a clue, and the children may suggest either stirring the fluids or spooning up a liquid and then pouring it back into the jar.

Allow ample time for a number of children to test each of the fluids using the spoons. Soon, the children will notice that some of the fluids are "runnier" than others. Let the children invent their own word equivalent to "runny" once they discover this property. Challenge the children to determine which of the four objects is the "runniest," which is next "runniest," which the next, and which the least runny. Ask for fresh volunteers to place the four fluids in the order of their "runniness," with the "runniest" at their right, and the least "runny" at their left. Continue the activity until several volunteers and the class are satisfied with the ordering of the fluids.

At this point you may wish to tell the children that scientists use a special word to describe the "runniness" of fluids. The word is "viscosity". Fluids with the *least* "runniness" are said to have the *greatest* viscosity. Thus the fluids are now arranged in the order of decreasing "runniness" from right to left, and in the order of decreasing viscosity from left to right.

Ask the children to verify carefully the ordering of the fluids. Pass out Record Sheet Number 1 so the children can record the results of the test by placing the appropriate symbols in the boxes. Ask them, for example, to check the fluids in the two jars at their left. Does the fluid at the extreme left really have a greater viscosity than the one next to it? Ask two volunteers to compare these two fluids and only these two. Ask the two children if they think they can compare better by spooning the two liquids in turn or by spooning them simultaneously. If instead the children have adopted a stirring method of comparison, encourage them to think about the value of using a "standard" stirring technique for all comparisons. Whatever the children decide will become the "official" method of comparison. Ask for two more volunteers to check the middle two fluids, one against the other, and still two others to compare the two fluids on the right. These tests are almost sure to agree with the original ordering because the liquids were chosen for their significantly different viscosities.

Now take this experiment a stage further and show the twelve extra marbles to the class. Ask the children if these marbles could be used to determine the different viscosities. The children may think of dropping a marble into a liquid to see how quickly it sinks. If they do not, ask the children to observe carefully while you drop a marble into the most viscous fluid. Tell them to suggest a method for comparing *two* fluids using the marbles. Exploring possibilities in this way, the children may well suggest dropping marbles into two jars of fluid *at the same time* to see which marble falls faster.

It is not important—nor even desirable—at this stage for the children to relate this test to the previous one using the spoons. It is important, however, that the children see the "marble test" as one way of making a direct comparison test of two fluids according to some common property. Repeat in its entirety a comparison, or "ordering," of the four fluids using the marble test. This provides you with a good opportunity to evaluate the children's understandings of the previous activity. When the fluids are properly ordered, compare the results of the marble test with the spoon test. The same ordering should be obtained. For some children this may clarify the idea that, in both tests, they were comparing the same property in two different fluids. Ask for volunteers to describe, if they can, the marble test in terms of the "runniness," or viscosity, of the fluids. Point out the difficulties in dropping two marbles at the same time.

At this point, ask the children to hand in their record sheets, which should be saved and returned to the children for reference at the end of the lesson.

Method: The approach is entirely experimental, incorporating individual and small-group laboratory activity, with many activities suggested for the home. The teacher commentary in each lesson lists objectives, supplies some subject-matter background, justifies the lesson, shows how it relates to previous and future content, and generally orients the teacher to his task. Each lesson has a detailed procedure which is to be varied as necessary by the knowledgeable teacher. All materials are listed, and the teacher is made aware of pitfalls and misapprehensions. This early warning system is feasible because these units have already been tested in typical classrooms.

In addition, there are work sheets on which to enter data, to draw structures, and to visualize ideas. These work sheets are supplemented by specially written stories, which incorporate important ideas and raise questions. Each unit includes one or more letters to parents, which explain the objectives of the unit and occasionally prepare the parent for activities which are to be done at home. The usefulness of this device may be judged by the letter to the parent on page ix of *Shape and Symmetry:*[45]

Dear Parent,

For the next few weeks your child will be studying a new MINNEMAST unit, SHAPE AND SYMMETRY. This unit is intended to give the child early experiences in handling abstract ideas such as "circular," "spherical," "triangular," and "symmetrical." Your child will learn to see the symmetrical arrangements of objects in nature such as those in leaves, butterflies, beetles, snowflakes, crystals and the human body. He will also learn how to test for three forms of symmetry: bilateral (or mirror), translational (or repetitive) and rotational (or turning).

The lessons will involve your child in looking at pictures, in painting, in learning rhythm in poems and songs and in constructing models of three-dimensional solids. Through these experiences an appreciation of the importance of symmetry is developed. It is also necessary to recognize where symmetry does not exist, so the child will learn to know why a figure is or is not symmetrical.

From time to time, your child will be asked to bring objects demonstrating symmetry to show to the class. These can cover a wide range from small

> toys to pictures culled from advertisements. You can help your child most during this period by looking for examples of symmetry in and around the home and in places where you go. Together you might observe the symmetrical arrangements of windows in an apartment building, the rhythm of a popular song, the regularity of leaves on a plant or the regular pattern in a wall paper design.
>
> In this way you will be complementing the more directed learning experiences which the classroom provides. Your participation with your child will be less formal and more leisurely and therefore add new dimensions of meaning and discovery to your child.

Evaluation: These materials were tested in the 1964–1965 school year in approximately 350 classrooms in sixteen centers. Teachers submitted written comments about the clarity and pertinence of the information supplied to them, their success and difficulties, and feedback based on observation. Research in developing achievement tests to expedite teacher evaluation is now under way. Objectives are usually carefully phrased in behavioral terms, although specific appraisal activities are not included. These objectives are much more specific in their application than the usual run of elementary-science objectives. For example, children are expected to know that "the identity of an object may be retained, even though some of its properties may change," in order that they may distinguish between reversible and irreversible changes.

Summary

In elementary science, there are at least two positions which one may take in deciding what and how to teach. On the one hand, there is a more or less unstructured curriculum, which fits the needs and capacities of the children and the teacher and is reconstructed each time the teacher has a new class. On the other hand, there is the K–12 curriculum, which on a national, state, or local level dictates what is to be taught and how long it is to take, offering teachers a minimum of choice. In actual practice, since science is not considered to be an important part of the elementary school teacher's job, he can often introduce as much variation as he desires.

We have made what we believe is a strong case for science instruction that is more in keeping with the first position than with the second. Nevertheless, we are well aware that few teachers are sufficiently prepared in science and sufficiently confident of their own resources and knowledge to create their own curriculum, and that, for practical and very understandable reasons, teachers need some kind of guide, some kind of structure which will help them and yet not force them into complete submission to its dicta. It is important for teachers to study the new curricula, which are of such immense promise because of their emphasis on process. Some of these curricula, the American Association for the Advancement of Science program, for example, are more highly structured than others, and the extent to which children will be handicapped if they miss parts of the program and continue with some of the more advanced parts is still uncertain. It may be that programs which incorporate lengthy skill and ability sequences are even more rigidly structured and less flexible than traditional textbook-centered programs. After all, there is really little actual need in traditional curricula for prior knowledge, despite their use of a spiral curriculum design. However, the goals and procedures of the new offer much of value. When school systems and teachers cooperatively convince each other of this value, they are ready to adopt the entire curriculum and to make it work. As John Holt says, "No important changes in education can be made that classroom teachers do not understand and support."[46]

The program which is closest in philosophy and in actual practice to the heuristic spirit is that of the ESS:[47]

> We have built many degrees of freedom into this unit [*Kitchen Physics*] and your students may be puzzled by its approach. They will hear many different explanations for the same observation. "Who's right?" "Is anyone right?"
>
> Even on the most sophisticated level, some of the questions raised will have no clear-cut answers. But this should not prevent the children from wrestling with them, nor should it discourage them from submitting answers on their own level.
>
> Science, after all, is both certainty and uncertainty. Its certainty—or better still, increasing certitude—develops out of earlier investigations; its uncertainty produces the questions that spur experimentation and analysis. You, as teacher, will have to tolerate (and help the children to accept) uncertainty and, perhaps, some unresolvable questions. It may be difficult, but it is essential.
>
> The order in which the experiments are presented was determined by testing and classroom experience, but, because of its built-in freedoms, we have never seen this course taught the same way twice. The first time you teach *Kitchen Physics* it might be wise to follow this order in a fairly structured fashion. Later we hope and expect that you will extend, shorten, modify, or innovate to suit your style.

The ESS units are more or less independent, and may be used whenever children are ready. Therefore, they miss the lock-step of the rigid curriculum, although there are tested sequences *within* each unit. The teacher is much freer to pick and choose activities because she need not worry about the prior capacity of her children to interpret data, to graph, and to classify, all of which are provided for in the context of each ESS unit.

We are deeply impressed by the new curricula, which have introduced new and exciting classroom-tested ideas and curricular sequences sufficient for the widest and most demanding selection. In accord with our philosophy, we advocate the process-centered programs, particularly those programs which are not so inter-locked and structured as to deprive the teacher of all initiative and freedom. Of course, the teacher may begin at any point in any program to introduce and strengthen the skills and content which are essential, but this will take much additional time. Unfortunately, the more successful the designers are in producing an integrated, sequential, tightly-knit program, the less freedom the individual teacher has to teach science to *individual* children.

For further study

1. What were the causative factors which led to the initiation of the new science curriculum studies?

2. How do these programs differ in intent and plan of procedure from conventional curriculum studies?

3. Investigate some of the elementary school science programs of regional and national scope that are not discussed in this chapter. Do they differ significantly?

4. Analyze a local school's science curriculum guide and contrast it with one of the new programs.

5. In view of these national studies, what function would you suggest for local curriculum development? What place for existing local science curriculum guides?

6. What are the implications of *Science—a process approach* and its thorough planning from K–6 for increasing rigidity in elementary science? Is rigidity less likely in the Science Curriculum Improvement Study program?

7. Analyze one of the programs discussed in this chapter in order to find out what themes, schemes, and specific information it incorporates.

8. What are the advantages and disadvantages of a single-content, high-level program such as the University of Illinois Elementary School Science Project, as contrasted with those of a comprehensive K–6 program like that of the American Association for the Advancement of Science?

9. Do these programs require a different kind of preparation and commitment on the part of the teacher?

10. Will a program such as the Elementary Science Study fit more easily into the existing framework of conventional curriculum structures than programs like that of the American Association for the Advancement of Science?

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We have assigned a high priority to science instruction that is born out of firsthand experience with the phenomena of science. The testimony of modern experimental psychology, buttressed by the collective wisdom of generations of classroom teachers, strongly suggests that the formulation of scientific percepts, concepts, and relationships is a direct function of interaction with all kinds of materials and situations, structured and unstructured. This declaration does not mean that children must learn by direct physical contact alone that Sequoia trees grow to skyscraper height or that acids taste sour. The vicarious modes of instruction described in Chapters 8 and 11 are indispensable in freeing children from the physical limitations of their classroom so that they may explore the farthest reaches of their world.

It is quite clear, however, that elementary school children have mastered neither the vocabulary nor the Piagetian formal logic that is required for predominantly verbal and abstract instruction. Therefore, the conceptual structure of science, which can quickly become abstract and detached from "common sense," must always be related to a concrete physical reality.

Why should a discussion of deserts, of inadequate rainfall, and of severe erosion be limited to far-distant regions, when in the local schoolyard there are small deserts whose aridity, surface temperatures, and limited life forms provide a splendid example, in miniature, of desert conditions? Why describe simple magnets when children may, with convenience and far greater interest, investigate the characteristics of magnets for themselves in the classroom?

7

Tools of learning—firsthand experiences

Most children are indifferent observers; however, they can be taught to be much better observers. But this kind of teaching is time-consuming; few teachers have taken enough time to make possible real growth in their students' observational skills. Traditionally, ability to observe is one of the objectives of elementary science, but in practice it is almost completely ignored. Teachers concede that skill in observing is important, but doubt that the diversion of time for this purpose is wise. However, time *can* be made available for the direct contact with reality which is so essential for children, if this contact is given precedence over the usual kinds of science content.

As a case in point, think of the bewildering vocabulary which confronts the fifth-grade child when he first encounters a textbook classification of rocks. He meets such words as metamorphic, sedimentary, and igneous; terms which are significant to the geologist, but mean little to him. He reads about minerals, quartz, mica, feldspar, sulfur, crystals, magma, lava, crust, pressure, limestone, and marble. His textbook portrays these terms by diagrams and photographs, but he often fails to see the relationship of the illustrations to the topic at hand. He finds it difficult to translate the picture of a particular specimen into its three-dimensional referent; or he may think that all specimens are like the superb museum samples in the color photographs.

The construction of reality by verbal processes, whether written or oral, is frequently impossible, because of the differences between the images which children visualize and the images which the writer or speaker is attempting to convey. There is no guarantee that physical objects, models, or field experiences will close this gap, for too much depends on the relevance or irrelevance of prior experience and of curricular and teaching emphases, and on the availability of the associated concepts. However, the search for direct experience is psychologically a step in the right direction.

The meaning of firsthand experience

Firsthand experience refers to non-verbal, non-symbolic activities that are directly encountered by the learner. They are direct, although not necessarily manipulative, contacts with a concrete situation. Experiments in which apparatus is manipulated so that a change may occur, demonstrations by children or by the teacher in order to elucidate some particular idea, and field trips for the purpose of gathering observational data—these are examples of firsthand experience. Obviously, much of modern science is beyond the reach of firsthand experience. The structure of science rests on a complex foundation of assumptions, inductive reasoning, and mathematical formulations, by which scientists organize a chaotic world. It is foolhardy indeed to insist that all science be taught by experiment or by field trip, because this inevitably results in a dead end. This is why such vicarious methods of instruction as motion pictures, diagrams, and models must be used whenever and wherever direct contact is not feasible. On the other hand, science instruction which is limited to vicarious learning, perhaps accompanied by verification experiments and activities, is a meaningless and illusory kind of science.

Inherent strengths of firsthand experiences

Few children can resist the urge to carry on experiments for themselves—to build, to change, to find out. The intrinsic strength of firsthand experience in stimulating boys and girls to venture deeper and deeper into scientific investigation is such that to neglect it is almost an act of vandalism. Despite our criticisms of traditional teaching by verification, it is amazingly effective in maintaining the interest of a group of children, simply because they participate. The fascination which binds youngsters to chemistry and microscope sets is direct evidence of the "manipulative" drive.

It is one of the tragedies of high school science that laboratory work is usually offered only to college-bound boys and girls. These youngsters, because of their socioeconomic environment and intellectual capacity, perhaps profit proportionally less from direct experience with the phenomena of nature than do those who, for one reason or another, are not in the college preparatory program. Perhaps the wrong youngsters are in the high school laboratories. Is there not an analogy to this in those elementary schools which encourage the brightest children (the gifted?) to participate in special science-opportunity classes while excluding the other children?

The differences in interests between boys and girls, which are well established in the elementary school years, appear to be culturally determined rather than inherent attributes of sex. No one knows whether a course of instruction which insists that girls as well as boys participate actively in science experiencing, demanding that girls investigate the world of science in the same way and with the same purposes, will eradicate these differences. It is a reasonable hypothesis that such a program will diminish, if not eliminate, divergences. Boys typically deal with boy's things—machines, motors, construction of all kinds—and therefore are much more likely to have an attitude which facilitates further meaningful learning in the sciences and their concomitant technology. Girls lack this experience, and thus are handicapped in courses such as physics which require both manipulative skills and physical-mechanical concepts.

These, then, are additional incentives for centering instruction in science on immediately accessible objects, phenomena, and relationships. It is imperative, however, to improve the ability of children to conceptualize and to incorporate these ideas into relational and propositional thinking. As they grow in their background of experience and in ability to think formally, children will combine both aspects of thinking. Learning from reading, talking, films, and all other sources of vicarious information will be more effective because of the continual interaction with their immediate environment during their earlier years.

Firsthand experiences supply the raw data to be classified, measured, and interpreted. When so used, they are part of the investigative or process-centered methodology. In direct contrast, there is the time-hallowed recourse to firsthand experience in order to confirm the accuracy of a principle or a textbook explanation. Investigatory experiences in elementary science textbooks tend to be supplementary. Indeed, all of the "experiences" can often be omitted from one of these books without appreciably altering either its expository course or its conclusions.

Verificatory activities are often helpful. They may be intrinsically fascinating; they may lead to paths of investigation; they may, finally, be presented as a kind of drill, a repetition of previous learning that the teacher believes requires reiteration. It is unwise to state categorically that *every* firsthand experience must lead to Inquiry, or that every verifying task is deadening. The teacher must select from his arsenal of "tools" whatever will accomplish the purpose he has in mind, and if he believes that an "experiment" taken directly from a textbook or manual provides the kind of thinking and practice he desires, he should feel free to use it. On the other hand, if his teaching is focused on the "inquiring mind" he will generally avoid activities whose specific purpose is verification.

Limitations

There has always been a conscientious effort in the schools to include direct experience with nature, both in and out of the schoolroom. Educators were quick to sense the immediacy and the power of direct contact with nature, but their efforts to root science education in the near-at-hand were overwhelmed by stubborn reality. School rooms, unequipped with even the simplest of apparatus, sources of heat, or even running water, were obstacle enough. And the community was apt to regard field trips as an evasion of educational responsibility.

Perhaps the Puritan ethic, the belief that what is enjoyable must be frivolous, has conditioned the universal identity of teaching with recitation.

These inadequacies, compounded by the insecurity that afflicted teachers who were forced to teach science, were sufficient to limit science to the textbook. Some of these difficulties still confront us today. Few elementary schools maintain a special science room. The unavailability of work space and science apparatus leads to constant frustration. Modern schoolrooms do have some counter space and running water, but the science corner, if it exists, is in competition with other space-demanding activities. Experiments may take days, weeks, or even months before reliable results are forthcoming. Children can rarely perform individual experiments because of these limitations —although it may be that *individual* experimentation for many children is not always a wise use of time and resources. Many schoolrooms lack minimal science teaching materials.

These are some of the physical limitations which restrict application of firsthand experimentation in the classroom. It is, of course, possible for the ingenious teacher to improvise and to borrow. Science supervisors are anxious to supply the necessary materials. The local high school may be prevailed upon to loan special items. Improvisation, on the other hand, desirable though it may be, is time-consuming, and notwithstanding the genuine advantages of home-made equipment, requires a certain ingenuity and mechanical facility. Frequent failure will dampen the enthusiasm of even the most highly motivated children, and this is precisely the result with home-made apparatus. For example, few children are able to construct a reliable electroscope, because of the inevitable struggle with electrical contacts. And there is *no* substitute for the microscope or magnifier.

Children encounter enough difficulty in interpreting what they see through a microscope without the additional complication of manipulating a toy microscope. A good micro-projector, available for about 150 dollars, is much more desirable than a quantity of 10-dollar microscopes which are often useful only in the hands of an expert. The teacher is not expected to dig out of the nearest clay bank enough clay for art and crafts instruction. Neither is she required to manufacture her own crayons. It is hardly reasonable to force her to rely on Pyrex milk bottles and home-made wooden stands in place of Pyrex beakers and iron stands with clamps. The gain in teaching effectiveness resulting from the versatility of commercial equipment pays for the additional cost.

Other limitations must be enumerated. Young children are awkward and limited in their manipulative ability. Their immaturity conditions the nature and extent of direct experimental activity. Class size also affects significantly the number and variety of such experiences. Many natural phenomena are not susceptible to elementary investigation. The necessary equipment may be too sophisticated, or the experimental results may be meaningless because they can acquire meaning only from a formalistic chain of inferential reasoning. Chemical experimentation, although inherently fascinating and often manipulatively simple, is likely to be meaningful only in terms of abstract theoretical structures. Therefore the study of chemical phenomena is generally unsuitable for children below the fifth-grade level. Biological experimentation is even more difficult than chemical experimentation. Indeed, experimental biology is not often encountered even in college laboratories, because of the peculiar demands of living systems and because of the number of variables which must be controlled. It is only in the realm of physics, the science of heat, sound, light, electricity, and mechanics, that elementary studies are relatively uncomplicated and reasonably clear-cut. It is for these reasons that the vicarious learning experiences of motion pictures, film-strips, television, and trade books must be readily available to both teachers and children.

Elementary school children who are unfamiliar with experimental procedures and unskilled in cooperative pursuits must be brought gradually into experimentation. They will need to learn when experiments are feasible, how to manipulate equipment in order to produce reliable results, and how to plan and work together. This learning takes time, effort, and patience. It can occur only if each teacher in the school provides suitable training and experiences so that children are gradually brought into higher levels of scientific investigation. The millenium will not arrive overnight. Its coming must be planned for and struggled for in every elementary grade.

We have stressed the obstacles which extinguish experimental activity in the elementary schools. These limitations are more or less restrictive, depending on the community, the teacher, the principal, and the physical facilities. It has been said that the teacher who is sincerely interested in providing firsthand science experiences will, by imaginative struggle, somehow be able to incorporate them into her teaching. All too often, this is moralistic, wishful thinking. The genuine obstacles which many teachers face are sufficient to quench the experimental fervor of a Faraday.

Inquiry by inquiring

It is a provocative albeit an unverified maxim that one learns to inquire by inquiring. Frequent opportunities, both incidental and intentional, for investigative instruction are therefore indispensable. The more frequent the opportunities, the greater the probability that process skills will develop. Touching, feeling, handling, and looking furnish the rich experiential background from which questions originate and their testable consequences flow. This is not to say that Inquiry teaching is limited to the raw data of the senses; but the immediacy of scientific phenomena provides the crude, easily accessible facts, often invisible to the neophyte, which are open to and which, indeed, call for the analytical and synthetic reasoning of practicing scientists.

Once again, however, the pitfalls lying in wait for the inexperienced practitioner of science "doing" must be pointed out. Recognizing and controlling variable factors, perceiving relevant changes, and choosing proper conditions are extremely complex and frustrating processes. The judicious teacher guides children along paths whose markers he knows, so that the children are likely to attain the rewards of reasonable success.

Group work

The difficulties of experimentation in the elementary school inevitably limit classroom investigation to group or whole-class problem solving. The teacher must choose between small groups or the entire class, for he alone is aware of each child's maturity level, manipulative skills, and ability to work both independently and cooperatively, and of the tasks which confront the class. It may be that in some first grades, each child will be able to investigate magnetic field interactions by experimentation with magnets and various materials. Following a class discussion which organizes their observations and develops hypotheses, the children may attempt individually to test the validity of these hypotheses. In other first grades, this procedure may lead to chaos. Small groups of young children can also explore the limitations and powers of their magnets, but their inexperience in working together is likely to lead to confusion. Working effectively in groups must be learned, and for this reason, even young children should have an ever increasing exposure to group assignments. One advantage of group involvement in an activity such as the study of magnetic fields is the ease of providing a few examples of many different kinds of experimental materials to the group, but it concomitantly magnifies the exertions of the teacher who must now guide a number of diverse "researches" instead of one all-inclusive activity.

The grouping of children for experimental science is on a different basis than is grouping for reading instruction. The latter is relatively effortless, because of the reliability of standardized tests of reading and because the task of the reading group is not that of working together, but of learning together. The diversity of skills, attitudes, interests, and abilities which children manifest in experimental investigation is quicksand for the unwary teacher. Therefore, whole-class activities are to be preferred for younger children, but should not exclude group and individual study.

Why attempt to provide small-group and individual investigative activities? Other important functions exist in addition to the admirable goal of improving cooperative skills. Ideally, teachers who organize science groups will meet with a few children at a time, and by listening to and questioning these children will be better able to guide and evaluate their progress. Small-group study, therefore, holds a promise of more effective individual learning. In addition, groups and the members of each group may learn a great deal about a particular aspect of science and pursue that interest in depth, because the groups generally investigate limited phases of the class topic. Because each group grapples with a different task, there should be a system for reporting so that the experiences and knowledge gained by each will be made available to all. However, experience teaches us that group investigation is not an efficient method of mastering facts and concepts, and it is justifiable only because mastery of science content is relatively inconsequential.

One type of group investigation, which has many advantages and yet suffers from few of the excesses of group investigation, is the "ad hoc" committee, which is commissioned during the course of the regular science period to find an answer to a class perplexity. This device is useful in many situations. For example, a committee report on perpetual-motion machines will add interest to the study of mechanical forces; a report on rocket fuels in the course of the study of motion will help clear away questions on how rockets work.

The teacher who strives to enrich science instruction by means of individual and small-group firsthand experience will soon discover that success is never guaranteed. When success is attained, it is because she and her children have taken the time to plan thoroughly the questions to be investigated, the means of finding answers, and the role of each child; and the groups have adhered to accepted rules for group work and for reporting their results. The teacher makes time for conferences with each group, so that she is informed of their progress, and, at the proper time, provides the encouragement and assistance necessary. Above all, the teacher must realize that the group process in the investigation of natural phenomena is not a natural outcome of child nature. She will have to strive for continual growth in its techniques, and each failure should contribute to a future success.

Experimentation

The educated citizen has traditionally conceived of experimentation as the prevailing mode of scientific searching. The phenomenal growth of science as a social and economic force in modern society began in the seventeenth century with the invention of an experimental methodology more or less as we know it today. In operational terms, experimentation may be conceived of as the purposeful variation of conditions, under rigid controls, in order to ascertain the effect of these variations. Experiments test hypotheses, which may have originated from earlier experiments, from theoretical reasoning, and from intuitive insights. The strength of the sciences arises chiefly from this capacity to test hypotheses. The results of an experiment may permit the formulation of an unequivocal vindication or negation of the hypothesis. Experiments in the classroom are experiments only if the child does *not* know the answer beforehand. Experiments should not be verifications of textbook laws. Verificatory activities are functional, but they are not experiments, because an experiment is equivalent to the exploration of the unknown.

Experience indicates that the experimental approach in the biological and the earth sciences is difficult for fourth- and fifth-grade children. Life forms are usually too variable and complex to permit a truly scientific approach within the limits of the elementary classroom; the techniques and equipment required for valid and reliable results are too sophisticated. Experimentation with the higher animals may require vivisection or other practices which are inhumane without special facilities and care. Vast domains of biology can be appreciated only after observation of microscopic sections and enlargement of small organisms; the limitations of child perception and interpretation of microscope images and the general unavailability of *good* microscopes are obvious handicaps. Leeuwenhoek, the great Dutch microscopist, saw a whole new world with his simple water-drop microscope, but he was a genius. It is too much to expect that younger children will profit from an inexpensive microscope. (See, however, the class-tested unit "Small Things," published by the Elementary Science Study, which is briefly described on p. 326, Chapter ten.) The earth sciences also suffer from a shortage of suitable experimental activities. Their phenomena may be exceedingly complex, or they may be meaningless without analytical (mathematical) treatment. The earth sciences are still primarily observational because of their complexity and because of the vastness of earth-matter and the enormous spans of time and distance to which they are inextricably bound. Of course, there is considerable experimentation in the biological and the earth sciences, but it is of a different order than in the physical sciences.

On the other hand, all grade levels may experiment with germinating seeds and test the effect of altering the kinds of soil, the amount of water, the kinds of seeds, and the position of the seeds; the growth of plants may be tested in many ways. And although similar activities with animals are more difficult, many elementary classes have conducted embryological studies with fertilized chicken eggs, studied the conditions under which fruit flies, ants, fish, and frogs grow, and organized and maintained balanced aquaria.

In the study of geology, the expansive force of freezing water, the erosive strength of running water, the layering of sediments, and the erosion-retarding ability of plants, to name but a few manipulative activities, are practical for younger children in typical classrooms. Although astronomy and meteorology are almost non-experimental, the physical concepts on which these sciences are founded are readily elucidated by experimental activities. For example, gravitational interactions and the effect of relative humidity on the dew point are easily illustrated.

But in spite of these exceptions, it is likely that firsthand experimental activity in the elementary schools is most practicable in the realm of the physical sciences. Firsthand experiences in heat, sound, light, mechanics, and electricity lend themselves much more effectively to the experimental approach, because of their relatively simple experimental demands.

Planning experimental activities

Simple experiments

It is almost platitudinous to say that the teacher should be thoroughly familiar with a variety of experiments appropriate for each field of science which his class will investigate. He must be aware of the purposes of the experiments, their relevance, and their conceptual and experimental values. There is no point in aimless experimenting, except perhaps that of interesting the class in a possible outcome. There should be a genuine question, a perplexity of some kind. Do frogs hop further on a warm day? Is it really possible to find out what the temperature is from the chirping of crickets? Why does a heavy iron boat float on the water? What makes a rocket ship fly?

The experiment, particularly if it is not completely explained by the teacher, is most appropriate if it is uncomplicated, affected by only one or two obvious variables, and is managed by easily controlled manipulations with ordinary apparatus. The teacher, as the guide, is responsible for projecting an agenda which is within the intellectual and manual abilities of the group. What at first seems to be a problem amenable to simple experimentation may prove to be exceedingly complex and far beyond the reach of most children. For example, it is enjoyable to play with a toy gyroscope and to sample some of its tricks, but only a physicist can understand in any but the most general terms the laws explaining the action of the gyroscope. To maintain a balanced aquarium, to change its environmental conditions, and to observe the relationships of plants and animals in it is stimulating and profitable, but scientific explanations for the changes observed are much more difficult to devise.

A not-so-simple experiment

Dissolving sugar in water and comparing the rate of solution of lump sugar, granulated sugar, and powdered sugar or the variation in the rate of dissolving as the temperature changes, is appealing, elegantly executed, easy to control, and yields clearly defined data. The effect of surface area on speed of solution appears to be direct and obvious, but is it? Are the fifth-grade children who easily perform the manipulations aware that the surface areas of equal weights of lump and powdered sugar are unequal? Do they realize that powdered sugar particles have surfaces? This experiment, designed to provide an answer to the problem "Does changing the kind of sugar change the speed at which the sugar dissolves?" is only a first step toward a solution, unless causal relationships are sought. Ultimately, at any advanced level of explanation, the electrical attractions of water molecules must be considered. It should be clear therefore that the utmost vigilance must be exercised by the teacher in order to avoid submergence in a deceiving experimental sea.

The key to a successful program of Inquiry experimentation lies in planning—in the cooperative outlining of an experiment or a series of experiments, and in the possible hypotheses, tests of hypotheses, and evaluation of results. This warning is repeated in this book again and again because of its urgency. Experiments extracted from a text or trade book are often expedient, but even so, their implications need to be thoroughly inspected.

Children must learn *how* to experiment. It may be that some individuals are born experimenters, but because there is both an art and a craft to planning and carrying out valid experiments, the teacher will discover that she will unavoidably subordinate results to technique unless her children have been properly prepared. The general techniques of Inquiry, the nature of hypothesizing and testing hypotheses, are described in Chapters 1 and 4. Children must learn, or better, begin to learn, how to select a representative sample, to choose the pertinent variables, to control experiments so that only one factor at a time changes, and to hold conditions constant. They can recognize that there are both implicit and explicit assumptions which condition every phase of an experiment. And there are manipulative skills to master—for example, using a wirestripper for removing the insulation from wire, focusing of a microscope properly, and heating a test tube without getting burned.

Safety

The teacher must also think of safety; the safety of his children is always of first importance. Experiments which call for razor blades or flammable liquids are best omitted or left to older children. The common use of "tin cans" for constructing telegraph sets is hazardous because of the sharp edges of the metal surfaces. Experiments in which 110-volt electric current may be directly accessible must, of course, be omitted. Indeed, some types of commercial equipment are improperly grounded, and, under certain conditions, absolutely unsafe.

Repetition

Experiments should be reproducible, and should almost always be replicated either by the same or by other pupils. Reproducibility is one condition by which the reliability of experimental work is evaluated. In addition, experiments are all the more valuable if they stimulate the generation of new questions, which may then be investigated, either by follow-up experiments or by reference to other sources.

Measurement

One of the most important experimental tools is measurement. It is desirable that from the earliest years of science instruction children be habituated to look for some measurable attributes in the scientific phenomena they study. Measurement requires mathematical skills which may not be available to the children and which must therefore be taught at the right time. For example, in the sugar experiment described above, equal weights in equal volumes of water at the same temperature are required; therefore, skills in weighing, in measuring volumes and temperature, and in keeping records are essential. Children will probably be unable to devise a technique for determining how much sugar actually dissolves until it is all dissolved. They may, however, estimate qualitatively the rate of solution by inspection, and by examination of the containers at regular time intervals until all of the sugar has gone into solution.

Whenever possible, therefore, the teacher should promote the application of quantitative tools in experimentation. Bar graphs are not beyond the competence of second-grade children. Older children may then build on this foundation in working with conventional coordinate graphs. Relationships are much more easily perceived from graphs than from tabulated data; prediction of effects caused by varying experimental conditions is simplified with graphic analysis, and the avoidance of algebraic equations minimizes one of the obstacles to quantitative thinking by children. As a case in point, the rate of growth of seedlings is easily visualized by bar graphs of seedling height. The flattening of the growth curve as plants approach maturity and the rates of growth of different seedlings are obvious. The differences in seedling heights will contribute to a better comprehension of individual differences, both in plants and in the measuring process.

Controlled experiments

Controls, frequently mentioned in this chapter, are defined in Chapter 1. Valid scientific experimentation requires controls, and, therefore, the omission of experimental controls weakens many experiments. Looseness in selecting meaningful samples and the overgeneralization which springs from improper sampling are often associated with this omission. There is little probability of perceiving cause-and-effect relationships unless there is some standard for comparison which is provided by a control. Consider, for example, the simple experiment in which the volume of a balloon changes as its temperature changes. In this experiment, a similar balloon kept at room temperature serves as the control. If one assumes that the air in the balloon is unchanged by heating and cooling, and if the control balloon is unchanged, it is justifiable to conclude that the change in volume is correlated with the change in temperature. If only one balloon had been used, this conclusion would be much less reasonable.

However, controls are often difficult to construct and to maintain, and it is defensible, *if* environmental conditions are constant, to assume that comparable results would have been attained were a control feasible.

For example, the ant is a fascinating insect to study. But the responses of ants to environmental changes—their reactions to different kinds of light, to chemical stimuli, or to temperature change—are meaningful only if the experimenter assumes that the only change has been in the particular interaction tested, and if, when the stimulus is removed, the ant colony returns to its previous state. Clearly, then, children should be aware of the premises that the *only* change was the intended change and that the results follow from *that* change.

Setting the stage

When children have not been trained in the Inquiry approach, the teacher will find that it is necessary to prepare them. No matter what their grade level, children who have had no experience in planning or carrying out non-routine experiments will come to the dead end of failure very quickly. The teacher must see to it that children have experience in analyzing problems; and for this, the whole-class approach to the analysis of problems is particularly valuable. He can set the stage for a simple, thought-provoking demonstration—turning a tumbler upside-down and plunging it into water, or crushing a can by creating a vacuum within it—and by judicious guidance, lead the class to formulate the problem, tender a variety of hypotheses, propose some ways of testing these hypotheses, no matter how crude, and decide whether or not these hypotheses are valid. In the process, he helps expose the assumptions, the illogical jumps, the overgeneralizations, and the lack of "controls" which are certain to arise.

It is essential to build up a feeling of confidence that these procedures, although slower and more awkward than reading texts, will result in a kind of learning which can come only from direct experience. In the words of Piaget:[1]

> We need pupils who are active, who learn early to find out by themselves, partly by their own spontaneous activity and partly through material we set up for them; who learn early to tell what is verifiable and what is simply the first idea to come to them.

Therefore, if the teacher can gradually build some of the necessary skills by relatively simple demonstrations in which the entire group participates, it should be possible for small-group work to follow. With younger children, small-group study will require a longer period of whole-class participation.

Physical-science experimentation

There is no dearth of ideas for experimentation. Many of the "experiments" in science textbooks are easily adapted to the kind of Inquiry experience of which we speak. *A Sourcebook of Elementary Science*[2] provides a sufficient number of uncomplicated science experiments for boys and girls at any grade level. Consider, for example, the experiment described below, whose goal is better understanding of an energy interaction scheme.[3] The materials are inexpensive: two alcohol thermometers, cellophane tape, cardboard, and colored construction paper. By properly cutting and folding the paper, several boxes of different colors are prepared, each holding a thermometer whose bulb is sealed within the box. The boxes are exposed to the sun after first being kept in the shade. The temperature of each box will be different. For comparison, the temperatures may be recorded on a "Heat Absorption Chart." (Metal cans painted different colors, or bottles covered with various colors of cellophane or filled with liquids of different colors, may also be used.)

The purpose of this experiment may be to introduce the study of heat or weather or to continue a comprehensive study of either of these phenomena. It may be introduced by asking the class whether it is better to wear white or black clothing on a hot day, or which becomes hotter, a concrete or a tar sidewalk. The ensuing discussion will probably end in a vote favoring white clothing and the tar sidewalk. Then the teacher should suggest that the class think up as many ways of answering the questions as possible. He may, if experimentation is suggested, bring out the prepared boxes, refer a committee to appropriate sources, or lead (follow?) the class in planning an original approach. Following the discussion, there should be a concise statement of what the class is trying to find out, a list of the suggested hypotheses, some tentative procedures, and a plan for recording data, accompanied by a collective willingness to suspend judgment at least until the results are in.

Of course, the teacher should not try to anticipate every disaster which may occur, such as improperly sealing the boxes or gathering data with thermometers which are inaccurate. The children should be led to see that the major difference between the boxes is in their color. They should find out whether heating for a shorter or a longer period than the fifteen minutes suggested in the original source makes a difference, and how long it takes for the thermometers to return to control temperatures. It is also interesting to compare the rate of melting of differently colored ice cubes or the rate of heating or cooling of differently colored gelatins. Still another variation of this experiment is to investigate the differences in the rate of ignition of differently colored papers heated by focusing the sun's rays through a lens.

Experiments like this are exciting. The challenge of predicting and testing the color that absorbs the greatest amount of heat will maintain interest. The experiment is controlled; it is semi-quantitative; it is reproducible; and it is within the ability of intermediate-grade children.

Naturally, its meaning depends on the underlying assumptions. For example, it is taken for granted that the only difference between the black and the other kinds of construction paper is in the dye, and that the absorption of light energy by the dye is the only change which increases or decreases heat transfer. Conceivably, extreme pressure may have been exerted in blackening the paper, which is compressing it so that heat conduction is more rapid. It is also possible that black dye molecules absorb energy more rapidly from colliding air molecules.

The teacher sets the limits of experimental induction. For instance, he may ask, "Does our experiment explain *why* one color is a better absorber than another?" This question is at the upper limit of explanation for younger intermediate-grade children, because explanations must now be given in terms of absorption and reflection of the various spectral components of light. In addition, the principle of differential absorption is implicated. If black absorbs *all* light energy, and if light energy is converted into heat energy, a black object must become hotter than a white object, which absorbs little or none of the light energy which falls on it. In all probability, the reasons *why* a black object absorbs light cannot be pursued very far, because the explanation will involve energy absorption by electrons and molecules, an abstraction which is unlikely to be meaningful to children below the age of twelve or thirteen.

The reader may reasonably question the value of an experiment such as that described above. After all, the information gained is trivial. Surely we all eventually learn that light-colored clothing is appropriate warm-weather garb; any child who becomes an astronaut will no doubt insist that his capsules be painted or covered with a reflecting material. Beyond this, the practical utility of this concept is minute. The worth of this experiment, however, lies in its exemplification of physical experimentation—the obligation to identify the problem and the assumptions, to propose and test hypotheses, to identify and limit variables, to measure and record data, and in time to assess the validity of the hypotheses. The experiment will lead to new questions and new directions of thought; the more man learns, the more he finds there is to learn.

Biological experimentation

Experimentation with animals or plants is more difficult than with inanimate matter. Clear-cut changes do not always occur when they are wanted, because many variables are closely intermeshed and because it is not always easy to keep plants and animals alive in the classroom. These are the reasons for the rarity of biological experimentation in the schools. Practical Inquiry experiments can be performed with living organisms, however; Chapter 12 describes several in detail.

In order to illustrate the nature of biological experimentation, we present an experiment appropriate for intermediate-grade children in any classroom. Turtles are excellent experimental animals, and the experiment described below is truly scientific.[4] Also, many children have purchased small turtles in variety or pet stores, and, after a few weeks of sporadic observing at home, have lost interest as the turtle slowly perished.

Once the "turtlearium" is established, children will spontaneously ask questions, which should be recorded for future reference: "How does the turtle swim? How does it walk? Does it swim all the time? Does it close its eyes under water?" These inquiries can be answered by careful observation. Questions on the effect of environmental or nutritional change can often be answered by experiments—for example, "What happens to the speed at which the turtle, a cold-blooded animal, moves as the temperature changes? Are turtles color-blind? Do they see or smell their food? How do they react to electric current?"

The teacher will presumably raise the question of temperature change and its effect on the turtle, and, with this stimulus, encourage his class to make suggestions for testable hypotheses and for suitable experimental procedures. Their suggestions for temperature control will probably include using a light bulb or an immersion heater, warming the water on a hot plate and then pouring it into the "turtlearium," and placing the aquarium in the direct rays of the sun. The teacher should, if no child mentions it, suggest lowering the temperature. "We plan to raise the temperature. Is there something else we can do to the water temperature?" This hint immediately evokes a proposal that ice cubes or ice water should be added. The experimental animals may be observed along with the proper controls, one or preferably more turtles at the ideal temperature. Some measurable index of activity must be selected. One of the most expedient is the number of times the turtles in the experimental and the control groups surface for air within a prearranged time period. (How long should this interval be?) Other changes in activity should be carefully recorded. The validity and reliability of the experiment are enhanced by exchanging control and experimental turtles and running through the experiment once again.

A similar experiment for comparing the effect of a good diet in contrast to an inferior diet may be worked out. The health and rate of growth of turtles (weight? length? vigor?) fed on raw hamburger, lettuce, raw chopped fish, or chopped earthworms may be compared with that of turtles fed on commercial turtle food. This experiment is likely to run for months, and the usual hazard of biological experimentation, loss of animals, is eternally present. If worthwhile results are obtained, the children may then come to appropriate conclusions about the importance of temperature and diet in the growth of their turtles.

Experimentation in the earth sciences

The earth sciences offer few experimental activities for elementary school children. Of course, it is possible to set up sand tables to compare the different rates of erosion by water flowing at varying velocities. Children may also investigate the dew point of the atmosphere, but this is not truly an experiment, for conditions cannot be deliberately changed. In general, elementary science must fall back on a series of chemical and physical experiments in lieu of "pure" earth-science experiments. For young children, the earth sciences are almost entirely observational and non-experimental.

One appropriate experiment for intermediate- and upper-grade children is the study of the sorting of earth materials in water. Sedimentary rocks are ordinarily formed by deposition of river-transported materials as the river empties into a large body of water, decreasing its velocity, or as the river slope changes. In many areas, school children will discover evidence of this kind of deposition in a neighboring field, or of a somewhat similar water-caused deposit on their windows. An appropriate first question is "Will a mixture of pebbles, sand, and gravel in water settle out if it is thoroughly shaken?" This question invites several hypotheses, which may be tested by mixing test materials and permitting them to settle or by pouring the mixture down an inclined trough and examining the resulting delta. Are the results the same? Are the particles which settle out most quickly in the jar the same as those which flow the shortest distance in the trough? Do the shaking time, the amount of sample and of water, the kinds of earth materials (e.g., mud as contrasted to gravel), and the slope of the trough have any bearing on the result? The answers to these questions obviously have some relevance to problems of soil erosion and, of course, rock formation.

Planning experiments

It is impossible to set down a rigid sequence of directions for planning, carrying out, and evaluating experiments. Because so much depends on the kind of experiment, the maturity of the children, their previous contact with experimentation, the facilities of the classroom, and the teacher's own confidence and skill in directing experimentation, an authoritative guide for this kind of firsthand experience is worthless. There will be some failures: failure to anticipate difficulties, to restrict what is attempted, to delimit, to examine the alternatives, to pose workable hypotheses and procedures, to keep records, and to develop efficient groups. For obvious reasons, the teacher must strive to keep these failures at a minimum, particularly with younger children. Frequent failure is demoralizing to children and teacher alike.

The list of general criteria which follows will assist the teacher in planning experiments and in evaluating their success.

Criteria for Planning and Performing Experiments

I. *The Problem.*
   1. Is the question answerable by experimentation?
   2. Is it clearly and specifically stated?
   3. Are the children interested in pursuing it?
   4. Which themes and schemes are involved?
   5. Can the class understand the concepts?
   6. Is the problem likely to branch out too widely or become too complex?
   7. Is experimentation the *best* way to find the answer?
   8. What assumptions do we bring to the problem?

II. *Hypotheses.*
   1. Are the hypotheses clearly stated?
   2. Are the hypotheses testable in class?

III. *The Experiment.*
   1. Can the experiment be performed with simple materials?
   2. Is it better suited for small groups or for the entire class?
   3. Is it safe?
   4. It is humane?
   5. Are the variables controllable?
   6. What measurements can the children make?
   7. What is the best way of recording the data?

IV. *Evaluation.*
   1. Will the same results be obtained if the experiment is repeated?
   2. Do the data positively dictate accepting or denying the hypothesis?
   3. Are the conclusions sufficiently limited?
   4. How may the conclusions be checked?
   5. Did the children grow significantly in ability to work together? To plan? To evaluate their results?
   6. If the experiment were to be repeated, what should be changed?
   7. Is the experiment worth doing?
   8. What new problems arose as a result of *this* investigation?

The demonstration

A demonstration is a manipulative experience which is performed in front of the class by the teacher, by a child, or by a group of children. It may be truly experimental, yielding a result not previously known to the class, or it may be verificatory or explanatory. In view of the importance of individual child involvement in manipulation and in directly perceiving concrete materials, the reader may ask whether it is truly a firsthand experience. But in any case, for some purposes and in some situations, demonstration teaching is exceedingly valuable, even though the child is not physically participating. For example, in order to provide guided practice in observation, the teacher may demonstrate a traditional elementary experience such as the "egg in the bottle," and then ask her children to tell exactly what they saw, movement by movement. A surprisingly large number of children, despite a warning to watch carefully, will miss much of what happens. Few children, for example, will see the egg bounce in the mouth of the bottle before it pops in. The teacher may tell the class exactly what she is doing, step by step, leaving the explanations for later. Or, she may say nothing, and slowly work through the demonstration, in order to test observational skill.

In addition to practice in observation, there are other sound reasons for demonstrations. Activities which require heat, particularly open flames, should be demonstrated. Primary-level children should not handle burning candles, canned Sterno, or Bunsen burners. Despite this, many "experiments" in textbooks and manuals list these heat sources. The classic experience with the burning candle, which is inserted base down in a pan of water and covered with a tumbler, is a case in point.[5]

In general, the teacher should do the work whenever manipulation that is beyond the ability of the children, or a series of simple manipulations, is required. Because of time limitations, as well as possible hazards and manipulative difficulties, the teacher may wish to lead the class himself.

A question which arises from discussion or reading can often be quickly resolved by demonstration. It is difficult, for example, for children to picture a vacuum. They grasp the concept much more readily if the teacher prepares a can with a vacuum, by boiling a little water in a sturdy uncapped gallon or two gallon can, permitting some of the steam to escape, and, after removing the can from the heat, capping it. If the can is sturdy, it will be crushed but not broken. The teacher should ask the class to listen when the stopper is opened. The children will hear a hiss as the can bulges out. This is evidence for the existence of a vacuum. If a second can, after crushing, is opened under water which is colored with ink or a food dye, the water will rush in to fill (or almost fill) the can. The presence of colored water inside is evidence that the water was not the original water required to prepare the vacuum.

This kind of manipulation is difficult for children, even though the theoretical explanation may not be complicated. But it gives the teacher a splendid opportunity to guide the thinking of the class by means of questions, hints, supplementary demonstrations, and special information. This Inquiry procedure is exemplified by the demonstration with the inverted tumbler of water, described in Chapter 4.

Demonstrations are particularly suitable for arousing interest and stimulating in children the desire to investigate an entirely new area of study. The exciting Bernouilli demonstration requires only a ping-pong ball colored on one hemisphere and inserted in a large funnel. The class will unanimously declare that blowing into the tube of the funnel will blow the ball right out. But the ball surprisingly stays in place, and the harder the teacher blows, the more firmly fixed the ball will be, even though it rotates faster. Indeed, it is easily possible for the teacher to turn the funnel so that she is blowing directly down the tube, the ball unsupported by the funnel, yet remaining suspended in air. There are many variations of this Bernouilli phenomenon which the children will be anxious to try, and from these firsthand experiences, accompanied by explanation and elucidation, children will be in a position to formulate a crude version of the Bernouilli principle themselves. They may also be interested in experimenting by themselves, either to see what happens as they change the original demonstration or to follow up some of the questions which arose during the demonstration.

An additional value of demonstrations must be mentioned: a minimum of equipment is required (although if instruction utilizes inexpensive materials that are readily available, this function is less important). In the upper grades and with more complex phenomena, demonstrations have proven to be exceedingly effective, although they are not equivalent to the firsthand contact with reality which individual or small-group experimentation provides.

The dynamic teacher who has learned how to prepare and carry through demonstrations will present exciting demonstrations. By his enthusiasm and inspiration, he can directly foster an interest in every area of science. If, on the other hand, the demonstration is merely a reiteration of what children already know, if it is presented in a monotonous, hesitating way, or if children fail to see what is done or why each step is taken, the demonstration will fail, and the potential for promoting growth in thinking, observing, inferring, and evaluating, as well as arousing interest, will be unrealized.

Some Practical Considerations in Preparing Demonstrations

1. The teacher should think through his reasons for each demonstration. He should test it before class use; if a group of children takes the responsibility, the group should be well-rehearsed.
2. The demonstration should be as simple as possible. The fewer the

pieces of apparatus, the fewer the steps, and the shorter the period of waiting for results, the more successful it will be.

3. The demonstration should be clearly visible to all children in the room. The apparatus should be large; scales for reading such data as weights, movements, and volumes should be oversize. Nothing the teacher does should hinder student visibility.
4. As the demonstration proceeds, the teacher should ask judicious questions to be certain that what is done is visible and that he is moving at an appropriate rate.
5. Demonstrating is an art. It requires skill, which comes only through practice. The teacher must project his own interest and excitement to make the demonstration provocative and dynamic.
6. If possible, the outcome of the demonstration should be unexpected and dramatic.
7. The demonstration is most valuable with a minimum of explanation and a maximum of stimulating questions. The "silent" demonstration is often effective if the children have had some experience in observing.
8. Whenever possible, student assistants should carry out the demonstration.
9. The purpose of demonstrating is to help children learn science more effectively and economically. Their needs must be kept continually in mind. The teacher should beware of excessive attention to experimental minutiae, to the detriment of the important aspects of the demonstration.
10. Student understanding is essential. Questions which children ask should be answered by other children as the demonstration progresses; the teacher should also ask questions in order to help children focus on the significant steps.
11. The demonstration is the creature of the demonstrator. There are no precise rules with which to operate. Imagination in devising or in selecting suitable demonstrations is essential. The teacher should not feel that the demonstration must be performed exactly as it appears in a manual or book. He should feel free to substitute and to improvise. Children frequently are able to devise variations which, for their purposes, are as good as or better than the traditional demonstration bill of fare.
12. The teacher should never assume that children all "see" the same events the same way, even though all are attentive; nor should he assume that they are all aware of the demonstrated phenomena. Analysis of the demonstration at its conclusion will reveal how much has been missed, and perhaps lead to a second trial.
13. The teacher must be willing to run the risk of occasional failure in

even the most carefully prepared experimental demonstration. Disaster sometimes provides an excellent opportunity to find out what went wrong, so that a fiasco may be turned into at least a strategic withdrawal.[6]

14. The analysis following the demonstration should elicit from the class the reasons for each step. Why is a funnel used in the Bernouilli demonstration instead of a cylindrical tube? Why is the ping-pong ball colored on one hemisphere? Can another kind of ball be used? Will another kind of funnel work? Smaller? Larger? Why is the mouth of the funnel open? Does the ball rest directly on the funnel? How does the ball change position as the teacher blows harder?

Many other questions may be proposed by teacher and children in order to explain what happens and to elicit new problems. It is plain that the Bernouilli demonstration and its subsequent examination is not designed to be neatly dissected and laid away to rest in a half-hour period. It *is* possible to do the demonstration in five minutes or less, to explain what happened in another five minutes, and to finish in not more than fifteen minutes. This, however, is not the kind of science teaching which produces the attitudes and abilities which we are seeking in elementary school children. If a demonstration, an experiment, a field trip, or a film is worth doing, it is worth doing well, and worth taking all the time necessary to develop it fully.

"Fully," of course, must be interpreted by the teacher. It may be that the treatment outlined above tells children more than they want to know or should know about the Bernouilli principle; if so, the teacher will decide just how far to go. If interest is lost, it is folly to wade on remorselessly. Better by far to drop the activity, summarizing it, and then to move on to something more rewarding, perhaps eventually to return after this failure has been forgotten.

In summary, we remind the reader that demonstration does not replace student experimentation. But student experimentation need not be, indeed cannot be, the only "laboratory" technique. Demonstrations are useful, but their use must rest on a sound pedagogy. Demonstrations may introduce a scientific concept, inspire interest, answer a question, verify an interesting textbook activity, or stimulate reflective thinking. Modern science is concerned with Inquiry. The demonstration experiment is one more pedagogical technique for building a sound, interesting kind of Inquiry learning.

The field trip

The third major category of direct experience with the world of science is the field trip. The field trip may be defined as an out-of-the-classroom experience, primarily for the purpose of observing natural phenomena which cannot be brought into the classroom or which, because of their immediacy, are best studied in their natural setting. In the elementary school, one would expect neither explanation of physical concepts nor experimentation to be a pertinent function of the field trip. However, in the realm of the earth sciences and of living things, the field trip is an exceedingly valuable educational device.

It is perplexing that children, who are outdoors so much, are aware of so few of the environmental phenomena which almost shout to them to stop and look. It really matters little whether the children live in a crowded city or a small village; there is so much to perceive and to investigate that is is almost impossible to exhaust local resources. Consider, for example, a unit in geology that includes study of rocks and minerals. In the city school, the class may begin with the rocks of which the room is constructed. Children may find in and near the school a slate blackboard, a man-made aggregate of cinder blocks and bricks, a flagstone or concrete walk, macadamized roads, granite curbstones, and marble steps. If the school yard is unpaved, there will be a variety of rocks, some rounded and water-polished, others angular and cracked, all waiting to be handled, broken open, and examined with a magnifying glass, and all with a history to be traced.

The school yard probably contains some perfect desert regions—hard-packed, sandy areas in which a few low, hardy plants struggle for survival, and on which a variety of insects scurry busily to and fro. Where there is a slope, evidences of erosion are usually clearly visible, accompanied by the characteristic alluvial fan composed of more or less well-sorted soil particles.

It is not necessary to think of a field trip as a "nature walk." A "nature walk" may be good exercise, but it is frequently not good instruction. Neither is it necessary to take an extended trip, when there is so much to see in the immediate neighborhood of the school. The trip should be planned so that relatively little walking is required. The center or centers of interest should be close together, and it is good planning to study thoroughly only *one* particular phenomenon. For example, a tree stump may make an effective lesson. Questions such as the following provide for an experience in observation and inference difficult to duplicate in any other way: "What kind of tree was it? What killed it? If tools were used, what were they? In what direction did the tree fall? How old was the tree when it died? Does it have any animal inhabitants? What kinds of plants grow on it?"

Teachers have always taken their children on formal field excursions, sometimes to great distances, to visit a zoo, a natural history museum, or a nature center. These experiences, if properly planned and followed up, are natural learning experiences and provide an incomparable learning environment. The informal neighborhood trip, however, is more likely to be productive, simply because it does not involve long distances and because the teacher and class can return repeatedly, collectively and individually, to re-examine what they have seen.

The trees in front of the school offer a real challenge. What kinds are they? What are their shapes? How do they differ from one another? How tall are they? How thick are their trunks? What is their bark like? Their leaves? What kinds of animals live in them? When do their flowers appear? Their leaves? How rapidly do they grow? Are they flourishing? These are but a few of the questions which may guide study.

How often have children viewed the environment only through the thick lenses of a textbook, while outside the entire living world waits for them! It is this direct entry into the world of nature, just outside their windows, which makes field trips so valuable for eager, active children.

Obviously, the teacher must be thoroughly familiar with the chosen site, and, if possible, he should visit it several times so that he may be cognizant of the seasonal and environmental changes. Because it is impossible to guarantee that conditions will always be exactly the same, he should anticipate possible deviations and be prepared to adapt his procedures accordingly. The precautions listed below will assist teachers in planning for worthwhile results:

Planning field trips

1. The teacher should know exactly what special purpose is to be achieved. He should visit the site one or more times prior to the trip so that he will be familiar with its educational possibilities and can plan his course of action. He should estimate the time for each part of the trip. It is often helpful to ask someone trained in the pertinent science to come along (e.g., a science teacher, a member of the local garden or bird club, an amateur mineralogist). Most communities contain a surprising number of individuals who are anxious to help children learn science and who will volunteer their time for this purpose.
2. The class should agree on some common-sense rules of behavior.
3. Children should understand the reason or reasons for the trip: *why* they are going out, and what relevance the trip has to their in-class learning.
4. If the class is large, the trip leader should concentrate on a few clearly visible centers. Children should be encouraged to return to the site, especially if it is near the school, in order to investigate independently, providing that they are old enough or are accompanied by an adult.
5. The teacher must continually look after the safety of his children. This is his *most* important task.

6. The teacher should try to take at least one parent along on each trip, particularly if the class is large and the visit is off the school grounds. If transportation must be provided, the school principal will make the necessary arrangements, which must include parental and school permission.
7. On extended trips, the teacher should arrange for toilet facilities, drinking water, and lunch.

There is no doubt that field trips are troublesome. They are often hard to arrange, and, if trips are novelties, the accompanying holiday atmosphere interferes with serious learning. At the conclusion of the day, the teacher may wonder whether the outcome was worth all the trouble.

The difficulty encountered is invariably aggravated on longer trips, for which transportation and lunch must be provided. The local visit, taking from fifteen minutes to an hour, is to be preferred. Few schools lack local resources which may be profitably explored at first hand. Even so commonplace an experience as tracing through the school the path of the steam generated in the boilers, or the electricity which enters from the outside utility line, enlarges the experience of youngsters.

Projects

Projects are special individual or small-group "researches," which have the particular function of enriching the scientific experience of individual children. They are particularly suitable for older boys and girls, who are able to work independently or cooperatively on tasks outside the realm of normal classwork, and who are motivated by a challenge to do something for themselves. It should be clearly understood that the incentive for projects should come from the child or the group. Projects must not be teacher-assigned, because they are then merely another kind of teacher-imposed task.

The value of the project arises from its child-origin, and grows as the child delves more deeply into his project. It may be as simple as a short report, either to the class or to the teacher, of an investigation into a class problem. It may be an entry for a science fair, an experiment or demonstration in which the child is interested, or the construction of a model which will help explain or illustrate a class activity. Whatever it is, the initiative must be the child's. The teacher's role is that of a guide who, because of her special knowledge, is able to refer the child to the appropriate school and community resources.

It will be necessary to provide working space and time for children who come from homes in which investigation is not encouraged. Because of this, and because success is not likely unless the child is self-starting and self-charging, few projects will be underway at any one time.

Projects are one way to provide for the science-centered children who are able to stay well ahead of the class in their formal science study, and who are ready for new opportunities. Obviously, the project must be so safe that the child working by himself is in no danger. It must be on a level at which success is probable. Even the most ambitious and hard-working child can undertake too much, with the strong probability that frustration will soon end the project.

The child who succeeds in putting together a terrarium that survives, who builds an exhibit of the simple machines, or who identifies the plants in his lawn demonstrates that he can surmount problems. He is more than a textbook reader or an able listener. His teacher also has an excellent opportunity to evaluate his tenacity, resourcefulness, imagination, and ability to synthesize knowledge in a non-classroom context. For these reasons, the wise teacher encourages some children to undertake projects.

Unfortunately, few children below the fifth-grade level are sufficiently advanced to tackle projects successfully. Indeed, in the sense in which projects are defined in this book, few children in any grade ought to be invited or permitted to attempt them. Most are not ready, nor is the teacher in a position to give enough of her own time.

Summary

The teaching of science in the elementary school must inevitably be experience-centered. Children lack both the multitude of direct interactions with natural phenomena and the psychological mechanisms which permit them to learn science by verbalistic and abstract instruction. Therefore, elementary science should arise from frequent, direct contact with the world of science.

This contact should include experimentation, demonstration, field trips, and projects. In addition to building a stock of sensory impressions and relevant information, such experiences are in themselves an intimate confrontation with the scientific enterprise. That is, children who study science by Inquiry are practicing, on their level, the same kind of investigation which has produced the knowledge and structure of science.

There is no simple organization which assures success in learning science by direct experience. Teachers will succeed only if they incorporate their understanding of how children learn into a deliberately organized Inquiry approach, whose goal is to help these children grow in their ability to hypothesize, to gather and evaluate data, to test their assumptions and hypotheses, and to come to reasonable conclusions. The core of this approach is the direct comprehension of nature which comes from a rich exposure to firsthand experience.

For further study

1. Why are firsthand experiences for young children believed to be so important in learning science?

2. Is it possible for scientific phenomena to be accurately and satisfactorily depicted by words alone?

3. In what ways can planning help to overcome some of the limitations of equipment and facilities in elementary school classrooms?

4. Must experiments in science be restricted to problems whose answers are unknown to the child? What are the advantages of verification experiments?

5. What implications do the difficulties in biological and earth-science experimentation have for first-hand learning of science in the classroom?

6. Is the statement "One learns to inquire by inquiring" justifiable?

7. What are some of the ways in which children may be grouped in order to expedite experimentation?

8. Are the authors contradicting themselves when they say, "It is impossible to set down a rigid sequence of directions for planning experiments," and yet list some criteria for planning experiments?

9. What are some of the approaches by which children may be taught *how* to experiment? Does this question imply that there should be more attention to sequentially organized curricula?

10. From textbooks, trade books, and courses of study, evaulate several firsthand experiences which pose potential safety hazards.

11. What are the implications of the new elementary-science curricula for preparing children to make and interpret experimental measurements?

12. Must children always be successful in science experimentation? (See the article by Barth cited in n. 6.)

References

1. Piaget, Jean, in Eleanor Duckworth, "Piaget Rediscovered," *Piaget Rediscovered*, R. E. Ripple and V. N. Rockcastle, eds. (Ithaca: School of Education, Cornell University, 1964), p. 5.

2. Hone, E., *et al.*, *A Sourcebook of Elementary Science* (New York: Harcourt, Brace, and World, 1962).

3. Adapted from "How Hot is Red?" *Nature and Science*, 2:11–12, September 21, 1964.

4. Adapted from Fletcher, Alan, "How to Keep and Study Young Turtles," *Nature and Science*, 2:6–7, January 18, 1965.

5. In this experience, the candle is firmly attached to the pan, usually with hot wax. The candle is lit, the water poured in, and the tumbler is placed carefully over the candle; the water rises and partly fills the tumbler. The common explanation that the water rises as a replacement for the oxygen consumed by the burning candle is incorrect. See Glanz, J., "The Burning Candle Experiment," *The Science Teacher*, 30: 29, November 1963. Because it is complex and is best explained as a chemical combustion in which large quantities of water vapor and carbon dioxide are released, this experience is probably not meaningful for children in the intermediate grades.

6. For an illuminating discussion of learning through failure, see Barth, Roland S., "Science: Learning through Failure," *The Elementary School Journal*, 66: 200–207, January 1966.

8

Tools of learning—trade books

For the child who likes to read, there is a never ending delight in the world of children's books. Casual browsing in the elementary school library, or in the children's room of the public library, reveals a treasure trove of science resources, with something for every child, whether he reads for sheer enjoyment or is seeking information to complete an assignment. Because of this very diversity and richness, however, teachers must be ready to evaluate science trade books critically and to sift those which are worthy from those which are second-rate. Many books written for children unwittingly distort or misinterpret their subjects, or they are uninspired and drearily composed. The major role of this chapter, therefore, is to present a rationale by which teachers can assess the quality of the trade books which are available to them and select those which are most useful. Unlike textbooks, trade books are not intended to make up the hard core of science instruction in a particular grade, but are supplemental, enriching and inspirational, and appropriate for more than one age group.

Few textbooks can engender in children a spirit of excitement, of anticipation, of enjoyment. Many trade books can. In addition to detailed information, special activities, and creative insights which are rarely encountered in textbooks, they are often written to stimulate children to learn more and to explore new horizons—in other words, to inquire.

As a rule, children should not be *required* to read informational books, for much of their charm and value lies in the option which children may exercise in book selection, and in each child's interaction with the book he selects.

This chapter will not deal with such sources of information as general encyclopedias, because teachers are generally familiar with their content and their value in extending textbook instruction. The special science encyclopedias, however, such as the *Young People's Science Encyclopedia*, are included because of their pertinence for Inquiry teaching.

Children's trade books may conveniently, although arbitrarily, be divided into five classes:

1. Direct experience.
2. Information.
3. Biography.
4. Fiction.
5. Periodicals.

Books of direct experience

There are literally hundreds of books and pamphlets currently available whose major goal is to open to children, both primary and intermediate, the fascinating world of experimentation and observation. Some are specialized, limited to a narrow content, such as Beeler and Branley's *Experiments With a Microscope*,[1] Harry and Laura Sootin's *The Young Experimenter's Workbook*[2] and Millicent E. Selsam's *Play with Seeds*.[3] Books such as these are invaluable because of their relevance to particular problems and because of the ease with which children can find appropriate activities for their science work. Unfortunately, specialized books are not published as frequently as books in which a few experiments or activities are suggested in each of several different sciences or fields of science. Rose Wyler's *First Book of Science Experiments*[4] and Harry Milgrom's *Explorations in Science: A Book of Basic Experiments*[5] are more or less typical of this latter group. Milgrom's book, for example, gives carefully detailed descriptions and some of the theoretical background for twenty-seven major, plus some subsidiary, experiments in such diverse areas of the physical sciences as sound, electricity, magnetism, fluid phenomena, mechanics, and astronomy. Miss Wyler's book ranges even further afield, by including a series of experiments in atmospheric phenomena, weather, plants, electricity, magnetism, chemistry, and light.

Books suggesting direct experiences are difficult to use in the classroom, because they lack specificity. In order to use them efficiently, the teacher must know their general content, so that he can suggest to his children the appropriate sources for their activities. In addition, direct-experience source books are valuable in the classroom only to the extent that they supplement textbooks and other available resources. A book which merely replicates activities, albeit in different words, is unlikely to be useful, and all too often general experiment books are replicatory. The book by Milgrom cited above is exceptional. It is a splendid example of ingenuity in devising unusual and delightful experiments which are easily performed according to simple directions. Books of direct experience have a long history, and the old standard experiments reappear continually, with little or no variation. The experiment book which is different, provocative, and accurate is rare.

Such general collections of activities have a place, but because of their limitations that place is not usually the classroom. They are often designed to interest children in performing experiments at home. The teacher may capitalize on this interest, however, by encouraging children to describe what they did at home.

Many of the books in this category are not focused on experimentation. These are observational books, such as Podendorf's *True Book of Weeds and Wild Flowers*,[6] by which children can identify common neighborhood plants, Sterling's *Creatures of the Night*,[7] which describes what to look for on a night walk, and Pistorius' *What Tree Is It?*[8] To a certain extent such books are informational and explanatory, but their function is primarily to motivate children to study their world by themselves and not merely to read about it. In other words, children are encouraged to break away from the narrow boundaries of a book-centered environment and to cultivate their own senses.

Information books

Information books comprise the largest single category of science books for children. Their purpose is to describe and explain environmental phenomena by presenting the appropriate facts, concepts, principles, and theories. Firsthand experiences are frequently provided for their illustrative and motivational power, but these experiences tend to be confirmatory, verifying what the book says rather than leading children to find out for themselves. As a result, information books sometimes are indistinguishable from science textbooks. For this reason, they may not be particularly attractive to children, unless they can satisfy a particular need. Children will turn to information books in order to find answers to questions when the answers are not in their texts.

Books for the classroom or school library must be chosen carefully, because they vary so widely in quality, accuracy, and detail. Even the inclusion of a book in a generally acceptable series, such as the *All About* or *First Books* series, is no guarantee of quality.

The information in books for younger children is often so meager that children are unlikely to find the answers to their questions in books which they are able to read easily. Information books for the intermediate and upper grades, on the other hand, are sometimes filled with unusual bits of information which are impossible to find in textbooks or even in the usual encyclopedia sources. For example, one astronomy book for children names the "Trojan planets," the small planetoids which move around the sun, both preceding and following Jupiter, at approximately its distance from the sun. Another lists more than one hundred nebulae included in Charles Messier's catalog of "celestial nuisances." There is probably no field of science, great or small, which is not touched upon in one or more of these books, and it is because of this broad coverage that they are so valuable in elementary-science instruction.

Adults as well as children can extend their scientific knowledge immeasurably by selecting judiciously from these books. The classroom teacher should feel no more hesitation in referring to these books for additional information than in augmenting her own resources for first-hand science teaching by consulting the experiment and activity books previously described.

Biography

Science teachers have traditionally sought to innoculate children with the spirit of science and an appreciation for the work of scientists by appropriate biographical reading. Although this may be the teacher's intent, biographies are not so single-minded. If they are to be read, children must first of all want to do the reading. Either the children must be anxious to learn about the man, or else the book must be so fascinating that, once begun, the sheer momentum of the narrative will carry the child along. Therefore, to sustain interest, biographers try to dramatize the scientist's story so that children will identify with him, will suffer and triumph with him, and will want to emulate him.

In the conventional, overimaginative biography, the scientist (or inventor) is poverty-stricken, rejected by society, and unable to obtain a hearing for his great idea. His long-suffering wife alone remains faithful to his vision. Such literary embellishments for the purpose of "humanizing" the great man are suspect if they detract from his ideas, methods, and achievements. Many scientists and inventors have undeniably suffered from abysmal poverty and triumphed over countless difficulties. Perhaps there is a moral to be discerned in their perseverance. Yet it is their intellectual legacy that is important, and, unfortunately, many biographies never do explain why their heroes were important figures in the world of science.

Of course, children look for a story line and are unlikely to be interested in isolated bits of information. Here, where the utmost skill of the writer is essential, is where most biographies fail. Scientists are individuals. Many have lived in quiet desperation; others have led adventurous and exciting lives. The majority, however, have created their own adventures in the realm of ideas. Only a writer of great ability and insight can transform the lives of men like Charles Darwin or Joseph Henry into narratives which are both accurate and provocative. The classic biography form, written for adults by historians, is not suitable for children, because they need a more intimate contact with the characters. Some kind of action, even if it is nothing more than invented dialogue, is essential. This biographical mode is acceptable, providing that the dialogue is plausible and its fictional origin is acknowledged, and that the story of the scientist's life illumines his times and his achievements.

Because of these restrictions, there are few good biographies of scientists, a striking contrast to the large number of biographies of soldiers, explorers, and politicians. It is difficult to enumerate more than a few books written for intermediate- and upper-grade children which set in perspective the work of Isaac Newton, Antoine Lavoisier, Humphrey Davy, Michael Faraday, James Clerk Maxwell, and Galileo Galilei, men whose genius has immeasurably changed the intellectual foundations of our world. It may be that their ideas are too difficult for any but the most gifted of writers to explain clearly to young children. In addition, some of these men led lives devoid of the military or political drama so familiar in the history taught in our schools, a history focused on men and deeds, not on intellectual pursuits. Furthermore, elementary-science texts and elementary-science instruction rarely single out the contributions of individual scientists, in contrast to the emphasis on the great figures of history in social studies. For example, in one contemporary fifth-grade science text of more than three hundred pages, only twelve scientists and inventors are mentioned, almost all as a device by which to identify certain principles, laws, or phenomena. Science is the intellectual creation of many thousands of men and women. Elementary science textbooks, however, treat science as if it were the necessary production of a vast, self-constructing, and nonhuman factory. Thus children are unlikely to want to know about the men and women who innovate in science, because to them science is not man-made.

Fiction

The genre of fiction in science books is of ancient lineage. It is characterized as fiction because, despite a strong dependence on accepted scientific knowledge, the author's imagination reaches far beyond these formal constraints. For example, writers frequently resort to fictional techniques in portraying animal life. The author describes in intimate and sometimes harrowing detail an animal's birth and daily struggle for existence. This close identification between the young reader and the animal creates an almost unparalleled excitement and interest. Unfortunately, this story-telling technique is often coupled with undesirable anthropomorphic and teleological elements. The animal appears to think and act as if it were human, meeting its problems of survival as if it were capable of purposeful thought. The best of these books, such as McClung's *Sphinx: The Story of a Caterpillar* and *Green Darner: The Story of a Dragonfly,*[9] are free of such errors. They succeed in combining the information which children seek with a strong incentive to continue to read after the information is obtained.

To the extent that a narrative is dependent on scientific ideas and relationships, it belongs properly in the category of science books. If, on the other hand, plot, dialogue, and "adventures" are overemphasized, the book is not primarily informational, and is more appropriately labeled as fantasy. The fundamental criterion is not how heavily the information is sugar-coated to render it more palatable, but rather the extent to which the story enhances the effectiveness of the book as a tool of scientific learning.

The reader should immediately be on his guard when he encounters the antiquated artifice of the bright-eyed youngsters, usually a boy and girl, coupled with an omniscient adult. Authors who employ this technique lack confidence in their ability to interest children and in the inherent attractiveness of their subject matter. They expect that interest will be aroused as their readers identify with the children in the story. To further stimulate their readers, they may improvise a series of implausible adventures, which deceive no one, least of all the young readers. After all, children read science chiefly for information; a strong plot with contrived dialogue and extraneous and unnecessary characters interferes with the search for answers.

This criticism is not intended to disparage books whose objectives are plainly literary and not informational. These books strive to tell a story, to develop characterization, to illumine the minds of children. They may have a scientific basis, but they are not science books. They may be categorized as "science fiction." Many fine examples have been written for upper elementary and junior high school youngsters. They are not, however, science trade books. Despite this somewhat arbitrary declaration, science fiction offers a potential for enrichment of instruction in the schools which is all but untapped.

Many children will turn away from science fiction, but those who are attracted to it are apt to be especially interested in science and in reading.

Unfortunately, there are few works of science fiction for younger elementary school children, although many books in the related class of fantasy are available. Fantasy and science fiction are both imaginative, free of earth-bound shackles, but science fiction is much more restrained, because it must be scientifically plausible in terms of conceivable physical and biological laws. Such books as Ellen MacGregor's *Miss Pickerell Goes to Mars*[10] and Williams and Abrashkin's *Danny Dunn and the Anti-Gravity Paint*[11] are delightful examples of science fiction written for children.

A provocative suggestion about the importance of science fiction has been proposed by Isaac Asimov, who estimates that fully half of the creative scientists he knows have read and enjoyed science fiction during their lives. Because this interest apparently begins in early adolescence, and because "interest in science is stimulated by reading rather than the reverse," Asimov argues that by identifying children who are interested in science fiction we will simultaneously identify a group of potentially creative scientists.[12] Unfortunately, science fiction has not always found literary favor in the eyes of teachers of English, and it is conceivable that many boys and girls are less apt to pursue this reading interest because it is derided and considered to be an illegitimate literary form, akin to comic books and the newspaper "comics."

The portrait of the scientist in science fiction is optimistic, favorable, and worth emulation. Science fiction frequently deals with the theme of a new world, a world which is shaped by the application of trained intelligence. For this reason, science fiction should be thought of as a worthy contributor to the inculcation of desirable scientific attitudes.

Sources of information for choosing science books

Obviously, it is impossible in this book to evaluate individual children's trade books in any detail, or to mention more than a few selected books. In general, the books which are evaluated are unusual either because of their quality and content or because they have been extraordinarily popular. The criterion of popularity is often questionable; if many copies have been sold, it may only mean that the binding and illustrations attract the adults who buy. Few adults are competent to judge a child's reaction to a book and the use to which the book will be put. Few books are popular with the majority of children who like to read. Most are unread, perhaps because they are unattractive, poorly written, or simply not known to the children. Others with a limited circulation may be extremely valuable to a few boys or girls. For example, a book on the aerodynamics of model airplanes will be indispensable to a few boys yet avoided by everyone else.

In addition, books may be filled with errors, false assumptions, and dubious generalizations, which, although not apparent to children, limit their value appreciably. Few of the publications which evaluate children's books employ reviewers who are sufficiently trained in science to point out errors and misinterpretations. As a result, children's science books are frequently reviewed in terms of attractiveness of story line and style.

It is impossible to keep up with the hundreds of new children's science books published each year. Books frequently go out of print, or are superseded by better books, and within a year or two the reviews are out of date. A detailed analysis of the criteria by which teachers may themselves evaluate children's books will help the teacher to make her own decisions for her class and teaching situation. There are excellent sources to which teachers may turn for preliminary screening of these books. There is no substitute, however, for examination of the book itself, difficult though this often is.

The most convenient evaluative source in libraries is the *Children's Catalog*, which is published every five years and kept up to date by annual supplements. Many children's books are listed with their suggested grade level, the price, the publisher, and a brief outline of the content. This outline, however, is often supplied by the publisher. In most cases, a short review from one of the children's book journals is also given. Specially recommended books are starred. The reviews tend to be terse, somewhat gentle, and uninformative, in part because the author's qualifications are rarely mentioned. The full review accorded books written for adults is rare.

Several sources of science-book reviews are cogent, informative, and critical. For example, Isaac Asimov's column in the *Horn Book* is delightfully written by one of the most competent contemporary science writers. Dr. Asimov is that rarity of book reviewers, a writer of children's books who is also a scientist. He is, therefore, unusually well qualified to testify to the merits, both literary and scientific, of the books he reviews. Because of the format of the *Horn Book*, however, it is a time-consuming task to find his review of a particular book, assuming that he has reviewed it. The books he mentions are those he approves.

Several additional sources are restricted in the number of books reviewed, but their reviews are of the highest quality because they are both uninhibited and knowledgeable. The reader may turn with confidence to the December children's book review in the *Scientific American* (principally of books for older children), the November review in *Natural History*, and the children's section of the *Library Journal*. *Natural History* is noteworthy for its critical analysis of a number of books of lesser quality in reviews written by specialists in the pertinent science fields.

Science Books, a quarterly review published by the American Association for the Advancement of Science, is more inclusive. In half a dozen lines, more or less, it summarizes the desirable and undesirable characteristics of books for readers of all ages. This source, like the *Children's Catalog*, employs the Dewey decimal classification, which increases its usefulness to libraries and facilitates comparison with other books of the same kind. Like *Natural History*, it is brutally frank, and therefore provides an element of criticism, which is uncommon in children's science-book reviewing.

In addition, each issue of *Science and Children*, published monthly by the National Science Teachers Association for elementary school teachers, contains half a dozen brief reviews. In general, these reviews are limited to books approved by a special committee of science teachers.

Many other sources of reviews are accessible, but few are written by individuals with scientific competence. Errors or misconceptions which vitiate the content of science books are much less likely to be discovered. Most reviewers are well aware of the dangers of animism, anthropomorphism, and teleology. Few, unless specially qualified, are likely to know that an author has accepted a particular theory uncritically or that the theory is discredited on the basis of new research. In many sciences, rapid change is inevitable, and a book which describes only the dust cloud theory of the origin of the solar system or which speaks of the atom as a miniature solar system is harmful. Only the scientifically literate reviewer is equipped to discover these inaccuracies and to identify them to the reader.

Criteria for evaluation

In general, criteria for selection of trade books for the classroom or for school libraries are much like those for non-science informational books, except that accuracy and recency are of the greatest importance. Teachers are well qualified to judge science books on all bases except accuracy and inclusion of contemporary research. Unless a review can be found in one of the sources previously mentioned, the teacher must rely on the qualifications of the author and the reputation of the publisher. In order to assist teachers in judging science books, the following criteria are presented:

The author

Writers with impeccable qualifications have written bad books; authors with minimal qualifications have written good books. These reversals are probably somewhat uncommon. An obvious first reaction to a new book is to question, "Who is the author? Why did he write it?

What special training or experience does he have which qualifies him to write this book?" Dr. Franklyn M. Branley, the author of many elementary-science books, is an astronomer at the Hayden Planetarium of the American Museum of Natural History. The teacher can be confident that *The Sun: Our Nearest Star*,[13] a book written by Dr. Branley for primary-grade children, will be well within the author's special area of competence and, therefore, scientifically accurate. On the other hand, the possession of a Ph.D. in physics does not give a physicist authority in chemistry or biology. For example, a recent book in chemistry written for intermediate-level children by a well-known physicist is filled with dubious and misleading statements. On the other hand, writers without formal training in science have, through research and innate ability, written outstandingly good books for children. Irving and Ruth Adler, for example, have written over three dozen children's books on such diverse and specialized subjects as air, numbers, rivers, the earth's crust, the ears, and the eyes. Dr. Adler, a mathematician, is an excellent writer whose books are well received by children and by scientists. Millicent E. Selsam, to cite another example, has written numerous books, many on natural history and experimental biology. Her formal science qualifications are certainly more limited than those of many other writers, but this has not limited the value of these books for children.

Occasionally, and less often than is desirable, publishers include on the dust jacket or in the body of the book a brief author's biography, which gives the reader some opportunity to assess his qualifications. If a scientist has been consulted, his name will usually be mentioned. Unfortunately, the reader almost never knows the exact role of the consultant or the reception accorded his suggestions.

In addition to determining the qualifications of the author, in itself an achievement of some magnitude, the teacher should consider the reputation of the publisher. No responsible publisher knowingly prints inferior books, although somehow such books do appear. In 1961, out of a total of 115 children's science books in the various fields of natural history, the editors found only 75 worthy of presentation to the *Natural History* panel of scientist-writers. This panel, rejecting 31 out of hand, reviewed 44 in detail, some quite unfavorably. In its words:[14]

> Publishers... are not living up to their responsibilities. One solution of the problem would be to employ trained science editors, specialists in the art of expressing technical ideas in straightforward terms. A few publishers have already taken this step. Another step is to draw on the experience of scientific consultants, although experience has shown that, by itself, setting up panels or boards of experts may not be enough. Consultants must be given ample time to consider manuscripts and

> illustrations, and to discuss details with writers and artists. Equally important, they must be well paid for their time.
>
> In the long run, more attention will also have to be paid to the problem of who is to do the writing. Relatively few scientists have the time and qualifications to present technical information simply and vividly; relatively few professional science writers have the background required for preparing accurate and balanced reports on progress in complex areas of research. An approach that has produced good results is the use of both specialists—a collaboration between scientist and science writer.

The millenium is not here. The established and successful publishers of children's science books must be given credit for good intentions and for attempting to ensure the quality of their books, despite their castigation by *Natural History*. Even so, the careful teacher will examine the critical reviews in appropriate sources before making any final judgments about purchase and use of science books.

The content

Many books are imitative, duplicating books already in print, and are apparently published because of mounting public interest in some scientific or technological advance. The multiplicity of books dealing with space, with astronautics, and with the planets is a specific example of this unfortunate, albeit understandable, tendency. Some of these books are excellent, some are acceptable, and many are inferior. They show evidence of hasty publication to reap the advantage of interest in the space effort. They also show a weakness in editorial supervision. In the space field, there are unlimited choices. On the other hand, in such fields as chemistry and plant physiology, few books are available for younger children.

Many books are extensive, ranging widely over an entire field, and incapable of providing answers to specific questions. These books are not suitable for Inquiry teaching because they are too general. They are not necessarily inferior, but they are not valuable in classroom teaching. Although there is, of course, a place for the inspirational or synthesizing book, the teacher should recommend books which foster depth of classroom learning—which are, in other words, directly informative.

What is important for this purpose? The book should contain a reasonably thorough treatment of some limited aspect of science, such as the microscope, elephants, or the sun. Within the straitjacket of fifty or a hundred pages, an all-embracing treatment is inevitably diffuse and superficial. In particular, the discerning reader will refuse to be impressed by titles which are arrogant and misleading. Books which are "all about" are not *all* about; the fact that many of the books in the

All About series are of high quality does not diminish the absurdity of their titles. Titles chosen to be striking and arresting are likely to be exaggerated. Books which begin with "The Wonder of" or "The Amazing Story of" are typically misleading.

Content organization

Is the information new to children? Is it likely to stimulate new learning, lead to new facts, new ideas, and new understanding? Significant duplication of textbooks or encyclopedia content is a sufficient reason for prompt discard. Does it stress ideas rather than a relentless accumulation of individual facts? Does it delineate the important scientific concepts, principles, and generalizations which give meaning to its subject matter? Important ideas are intrinsically interesting and are ignored only by writers who hold an antiquarian conception of child mentality. Children *are* interested in the many facts which so commonly fill children's books; they delight in the interesting but trivial fact that the diplodocus was probably the longest animal which ever walked the earth. But they should also know how the diplodocus fit into its ecological niche, the adaptations by which the species managed to survive for many thousands of years, and the interplay of complex forces which led to its extinction. Concomitantly, they should understand the role of the paleontologist in establishing the facts and assumptions which have led to the modern conception of organic evolution. A book which interweaves these threads of fact, assumption, principle, and theory is infinitely to be preferred to a compendium of isolated facts.

Are the concepts within the intellectual grasp of the class, or of the children who will read the book? If Bruner's contention that no concept is too difficult for children to grasp at some intellectually honest level is valid, clarity and accuracy of conceptual statement become vital. This is yet another argument for intensive writing. Building a concept from its first rudimentary meaning to a more sophisticated and abstract notion is not a task for the hasty and superficial writer. The difficulties are compounded by the requirement that the limitations and uncertainties of scientific knowledge be made clear; this can only be done by the writer who intuitively knows how much is just right.

Is the book up-to-date? Enormous changes have occurred in many fields of science within the past decade. Much of what was taught as scientific gospel a few years ago has become obsolete. The tremendous strides in nuclear physics, biochemistry, data processing, and genetics will serve as specific examples. Less dramatic revolutions have occurred in such fields as animal behavior and microbiology. The practical sciences of engineering, medicine, and astronautics have been dramatically transformed. A book which was the last word on rockets ten years ago is now antediluvian. Certain classes of books, however, have hardly aged. Many books of experiments, of plant, animal, and star identification, and of natural history, despite publication a decade or two ago, are still useful and interesting. They may be somewhat more slowly paced than contemporary works, and their age is often revealed by their illustrations.

Above all, science books must be accurate, in their facts and in their interpretation of these facts. One of the most serious deficiencies of many science books is the unwitting inclusion of serious factual errors, either because of carelessness or simply because the author does not know better. For example, one chemistry book refers to H_2SO_4 as a chemical symbol rather than as a chemical formula, and it describes atoms as miniature solar systems, a common but incorrect mental model. Perhaps these "errors," committed in a good cause, are not serious, but they are troublesome misinterpretations, and lead to doubts about the author's competence. Books often equate mammals with animals, and refer to "insects and animals" or "animals and birds." Many astronomy books explain the orbits of satellites, moons, and planets as the resultant of centrifugal and gravitational forces, disregarding the non-existence of "centrifugal force." Even experts in a scientific field are capable of error. Reviews of texts and monographs written by scientists are often critical of incorrect statements and interpretations which the reviewer has discovered. Mistakes in books written for specialists are less harmful than in books intended for the general public, however, because of the special competence of their audience.

In addition to the incorporation of gross errors, there is often an implicit (sometimes explicit) acceptance of teleological, anthropomorphic, and magical ideas, despite the scientific consensus that animals and plants are not governed by ideas of purpose. With the exception of man, living forms do not, consciously or unconsciously, plan in the human sense. For this reason, to speak of plants "liking" dry, sandy soil, or of field birds being dull-colored for purposes of camouflage, is an unwarranted extension of human motivation. To explain animal actions as "instinctive" is also questionable, and modern animal behavior studies reject the term.

Some children's books capitalize on sensational, morbid, or exciting headings—"Funeral of a Town," for example, is a heading in one book on volcanoes. They breathe magic, mystery, and wonder as they overdramatize science. It is hardly necessary to shout to children that the life of an ant colony is "amazing!" and "mysterious!" Exciting and provocative, yes, but hardly amazing. The book which gives such chapter titles to the discovery of photography and the invention of the telephone as "The Mystery of the Chemical Cabinet" and "Magic Messengers" is guilty of a literary misdemeanor.

Experiment books

There are many collections of science experiments on the market. Some are devoted entirely to experimentation and to firsthand investigation; others merely include a number of activities in their narrative, in order to interest and intrigue children and to add a concrete-empirical referent. Although some experiment books are hastily compiled, routine grab-bags of standard experiments like those in science textbooks, many present truly ingenious experiences for introducing children to the kind of learning which is the heart and soul of modern science education.

Two broad classes of experiment books exist—the first describes every step minutely, prescribing apparatus and technique in paralyzing detail, and explaining the implications of the experiment (although many do not discuss these implications). These books, by far the most numerous, leave nothing to the child except the task of verification. The second class is written to challenge the child, to present him with questions which will lead him to a new awareness of his world, and to suggest the multiplicity of pathways by which scientific knowledge may be gained. These books, by virtue of their design, are particularly well adapted to Inquiry teaching in the classroom, although teachers can adapt the "tell-all" experiment books by presenting these experiments as demonstrations, without their explanations.

Teachers should examine experiment books closely before recommending them. Children who follow the directions in some books, particularly those including chemical experiments, may actually be in serious danger. Experiments with commercial muriatic acid, a hazardous acid for children to use, are sometimes recommended. Other books require pieces of "tin can" metal for a telegraph sender, without warning their readers that the edges of these pieces are razor sharp, capable of inflicting severe cuts. The teacher should also be suspicious of experiments which depend on 110-volt current, sharp instruments, or fragile glassware, especially if his children must work at home without trained supervision.

In addition to these potential hazards, many experiments are valueless because they are either uncontrolled or poorly controlled. This is, perhaps, an unimportant criticism. When experiments exist only to add a little frosting to an explanatory cake, when they are not intended to cultivate in children either desirable attitudes or skill in scientific investigation, this is, perhaps, an unimportant criticism. But when a causal explanation is sought, when a variable is changed, the potential for valid explanation and for securing meaningful data is enormously enhanced by controlled experiments. Whenever an experiment is too complex to duplicate conditions sufficiently for proper controls, authors should clarify for their readers the assumptions and weaknesses of their experiments. This necessary safeguard is not often found in experiment books. The other criteria for effective experimentation, such as the need for adequate sampling and the insufficiency of one experimental trial, should also be applied to experiment books.

Still another weakness of experiment books is their tendency to tell "how something happens" (e.g., "how plants obtain water," or "how rockets work"). Titles such as these are misleading, because no real explanation is given; in its place, there is substituted direct experience of the phenomenon itself. Colored water rising through the xylem of a celery stalk is an observation; it does not show "how plants obtain water." If, through experimentation, the child learns that water passes by osmosis and diffusion through cell walls, and rises by means of osmotic, capillary, and transpirational processes, then and only then will he know something about the "how" of water movement in the plant.

The "tell-all" book, to fulfill its role of home instructor for the child who is *not* a creative experimenter, must obviously provide lists of easily constructed or readily available supplies and equipment; it must be well-illustrated, lead to swift success, and give simple, accurate explanations. Unfortunately, a book of this kind may be a dead end for its readers, because it will lead them to think that they have learned all that is important and that little remains for the future. At the very least, additional suggestions for investigation should be provided, supported by appropriate references.

George Barr's "Research Ideas" series,[15] written for the child of ten or older, is a splendid example of the second class of experiment books. There is a detailed and intriguing table of contents, a complete index, clear and interesting explanations; the bulk of each book contains problem-experiments and questions whose answers can be found only by relatively unstructured experimentation. Several suggestions for further information are appended to each section. These books are singularly appropriate for Inquiry teaching. Their freedoms should be contrasted with a well known experiment book in which children are directed to prepare hard water, and to compare its behavior with soft water when soap is added. The writer not only announces that the soft water will form no curd, but that there will be a curd at the surface of the hard water sample.

The incorporation of scientific theory or hypothesis in explanations is often without any reference to its hypothetical and frequently questionable basis. For example, the cautionary remarks "Many scientists believe..." or "One of the hypotheses which many scientists accept is that..." are not commonly included in discussions of the age of the earth or magnetic domains. On the other hand, many experiments are never really explained. One of the best-known experiment books, which in selection and style is superior, omits explanations. The experimental description merely ends, although a few practical examples may be appended. In one experiment, which fails to give even a hint of the implications of controls, an ice cube sprinkled with salt melts more quickly than a control ice cube. The result is equated to the melting of ice on roads and sidewalks by addition of salt. But, the child is given no explanation. Although explanations are necessary in many books of experiments, they will be meaningless if they are not gradually and systematically developed in the appropriate context. For example, in a book written for intermediate-grade children, the magnetization of a needle is explained in eight lines by the Weber-Ewing theory of magnetism, which dates from 1891. There is not a hint of modern magnetic theory.

Vocabulary

Not only must concepts be set in a matrix of exposition, the vocabulary employed by the author must be carefully selected. Of course, many new words will be introduced. It is possible to write science without technical words, but it requires many circumlocutions, approximations, and explanatory overloads. It is much more convenient to define each technical word, either formally or informally, when it is first used. The long or unusual word is not in itself discouraging. The overuse of technical words for their own sake is. To write about dinosaurs without giving some of their names, or to describe space travel without the words "light-year" or "galaxy" is incomprehensible. And how can hearing be explained without the words "decibel," "cochlea," or "Eustachian tube"? Each science has its own species of jargon; one of the first tasks that confronts prospective scientists is that of mastering the language of their specialty, which will otherwise be incomprehensible.

Some writers deliberately limit themselves to words which they assume are within the grasp of their readers. But the difficulty which authors encounter in writing compelling and vigorous prose with a restricted vocabulary may outweigh its advantages. Writing down to children is not an answer, because children soon recognize this form of condescension. Writing for children is not merely a matter of translating an adult book into simplified language. Complicated ideas are not explained better by avoiding technical terms or by forcing on the reader such unrealistic analogies as the solar system atom model, which has become a cliché of scientific writing for the layman. The words which are used must either be familiar or at least be convertible by familiar words into the desired mental imagery. Difficult ideas become meaningful as they are developed in context, built by fusing simpler previously known ideas into new hierarchies of understanding.

Irrelevant and unimportant facts, interesting though they may be to the casual reader, make no contribution to the exposition of scientific concepts and principles. For this reason, the best books for children tend to treat one, or at most a few, topics, each at length. Except, perhaps, in the realm of taxonomic and descriptive natural history, a framework of principles, relationships, and interpretation of facts will contribute to the longevity of the book. Facts rapidly become obsolete; principles are more resistant to change.

Writers who dwell on the curious, on the unusual, or on the accumulation of facts without building steadily to higher levels of thought, trusting that in this way they will maintain the children's interest, are making a mistake. Children do search for facts. But although factual books interest them, isolated bits of information do not contribute educationally.

Children tend to disregard books in which the information they seek is sugar-coated—that is, embellished by trite stories, by stock characters, or by the author's own responses. Dialogue has a tendency to get in the way of the story line without serving a useful function. Teachers should beware of writers who talk of "wonders," "marvels," and "mysteries." Children are not interested in "good" or "bad" animals or in morals drawn from nature. They tend to shun books in which information gushes forth from adults or precociously knowledgeable children. Any story which is a transparent device for presenting information is suspect.[16]

From the viewpoint of value for the classroom, teachers should look to books which encourage children to think for themselves, which ask questions and suggest direct ways for children to find answers to these questions. Desirable books explain how scientists study nature and clarify the forces which drive scientists on. These books will distinguish clearly between facts and hypotheses, between plausible and implausible hypotheses, between theory and practice, and between assumptions and experimental and observational data. The books which open new vistas, stretch the mind, and liberate the imagination are especially desirable. This invitation to Inquiry is a particular strength of science fiction, and is shared by many of the best information books for children. A book whose subject is the stars may be nothing more than a collection of star characteristics. It will be enriched by the inclusion of stellar evolution, a subject that is known to few children but is of great significance in placing man in his universe. There are few fields of science which are so mature that they harbor no unknowns or are without contradictory and confusing elements. Surely one function of children's books is to lead children to see how much more there is for them *and* for scientists to discover.

Style

A book may be exceedingly useful to children even though the writing is pedestrian, if it helps children find answers to questions. As a result, generalizations about writing styles are difficult to make. Of course, a writer should avoid involved, highly technical language in favor of clear, direct, straightforward exposition. His expository style should enhance the ease of reading and understanding of the age group for which the book is intended, but children's reading levels and the backgrounds are variable and unpredictable. A book which is advertised for grades 4–6 may be profitable to bright fourth graders; slow sixth graders, on the other hand, may be able to use it only if they are sufficiently motivated. The gifted writer of children's books is able to excite children, to inspire them to want to learn more. Unfortunately, there are few writers who meet these specifications, just as there are few writers of adult science literature who are, in the best sense of the word, popularizers—men who write vividly, clearly, and accurately.

Humor is often desirable, both in the body of the book and in the illustrations, but humor by itself is no substitute for insight. Humorous touches must not interfere with the narration. Short sentences with a minimum of digressions and definitions add vigor and enhance the potential of the book for younger children. Figures of speech should come out of the child's experience. Many books appropriate for children in a middle-class socio-economic-level school are meaningless to disadvantaged children who have never wandered through a woodland, observed the sharpness of a dark night, or attempted a scientific experiment at home.

It has been suggested that a brief overview be given at the start of each major section of a science book. From a psychological point of view, this seems desirable, although there is little evidence that an introduction of this kind is actually helpful. Few children's books use this organizing device consistently.

Rachel Carson has proven that science books for children can be sensitive and poetic in feeling and language, but she was a splendid exception. Children's books which make their points directly and clearly, beginning with familiar experiences, will be sufficient to satisfy their young readers.

Illustrations

In addition to factual errors, children's science books often have mediocre illustrations. The function of illustrations in science books is not primarily esthetic; rather they should supplement the text by visual explanation or description. More often than not, illustrations are garishly overcolored, almost as if it were necessary to establish the book's *bona fides* in a color-mad world. Color is often essential, either to accentuate certain points or to enhance the fidelity of the illustration, but color for its own sake is useless.

Some illustrations are so encumbered with details and labels that they bewilder the reader; others are equally frustrating because they are unlabeled and enigmatic. The value of illustrations is increased if they are intimately integrated with the text, both physically and conceptually. There is nothing more irritating than to be forced to search through a book for a relevant diagram. Stylized and unrealistic drawings, devoid of the slightest hint of scale, make it impossible to visualize that the object pictured is as big as an elephant or as small as a doll. Illustrations which are either scientifically inaccurate or which directly contradict the text are not difficult to find. Or they may be unsuitable at the age level for which the book is written, perhaps because they have been copied without adaptation from books written for adults. An added dimension of realism is available with photographs, but photographs should be used only if accuracy of representation is essential. Otherwise, the versatility of the specially prepared drawing is preferable.

Inferior illustrations, which add little to the text, indicate a lack of editorial supervision. In books which are marred by this defect, the writing and art work have been artifically separated by the publishers, who keep their authors and artists apart.

Mechanical factors

It is a truism that a book should not be judged by its cover, but when children are browsing, looking for something interesting to read, they are often tempted by an attractive cover. Publishers are well aware that striking dust jackets and attractive bindings help to sell books. However, when books are purchased to supplement science instruction in the schools, their external charm is less important, because children go to these books for the information they contain. Books for use in schools must be sturdily bound and, therefore, will be more expensive than books for home use. Books for young children should be big enough to hold comfortably, and should be printed in a type size sufficiently large and well spaced to make reading easy. It is surprising how many books run on endlessly without a break in the flow of narrative, even when the topic changes sharply.

Some authors have succeeded in extending the reading levels of their books by writing separate but concurrent texts. For example, opposite each page in his *What's Inside* series,[17] Herbert Zim places a diagram or illustration written for younger children; on the next page he supplies additional information in smaller print for older readers, parents, and teachers. The *Young People's Science Encyclopedia*[18] provides a descriptive introduction for third or fourth graders in its entries, and an amplification in a smaller type size for children up to the ninth grade. This device is obviously helpful in extending the range of an expensive encyclopedia, although depth of explanation for younger children is sacrificed.

Another mechanical factor which should be considered is the presence of the appropriate bibliographical apparatus. The omission of an index should be compensated by a detailed table of contents, although if the book is a potential reference source, a detailed index will be helpful. Even if the definition and pronunciation of new words are given when they are first encountered, a glossary and pronunciation guide are indispensable. Incorporation of references for the reader as well as the references on which the author relied is also desirable. Certainly, if books are intended to stimulate new ideas and new investigations, their authors should encourage children to pursue further learning. These references will benefit teachers and parents as well.

Bibliographical aids cannot compensate for errors of fact or for stylistic shortcomings. They will, however, make it possible for children and teachers to exploit the potential of books more fully. Because elementary school children are just beginning to use references and to search for information in school and public libraries, the inclusion of bibliographical aids is even more imperative.

Children's science periodicals

Nature and Science, *Science and Children*, and the *Cornell Science Leaflet* are of major importance in elementary-science education. *Nature and Science* is published for the American Museum of Natural History by Doubleday and Company on a twice-monthly schedule, with monthly issues in September, May, June, and July.[19] This periodical, remarkable for its content and level of writing, is available in a teacher's edition and in a separate edition for children. Its format is exemplified by the

September 20, 1965 issue. The lead article, "A Treeful of Butterflies," is a two-page spread on the life cycle of the monarch butterfly. Three pages are given to "My Friends, the Raccoons," followed by an ingenious investigation, "How Hard is the Soil?" There are two pages on space suits; a page of science puzzlers; the first part of a two-part article on "The Fly," which will stimulate children to embark on a simple investigation of fly behavior; one page on the "Pop-Gun Plant," which explains one mode of seed dispersal; and, finally, a page on "Combination Locks."

In the course of the year, the magazine covers the gamut of science in authoritative and fascinating articles written by experts. The editorial bias is clearly shown by the fact that many articles which are not specifically experimental suggest firsthand activities. The illustrations, both drawings and photographs, are well selected, relevant, and informative. The teacher's section, usually four closely printed pages, is crammed with suggestions for enrichment and with supplementary information.

The *Cornell Science Leaflet*,[20] a quarterly magazine published at Cornell University since 1896, is probably the oldest continuously published children's science magazine in the United States. Its emphasis is still somewhat heavy on natural history, but at least one issue a year is devoted to the physical sciences. Because it is well written, up-to-date, and on a high level of scientific competence, it is an excellent reference for children and for the school library. Many suggestions for direct experience are given, and, as a result, it is singularly appropriate for Inquiry teaching.

The range of subjects is illustrated by the thirty-two-page issues of 1964. The January number, "Round and Round," was concerned with forces and circular motion; the March number was devoted to nature poetry; the May issue was "Liverworts and Mosses"; and the October issue dealt with microbes.

Science and Children,[21] published by the National Science Teachers Association, is the official organ of the Council for Elementary Science International. It averages thirty pages in each of its eight issues per year. Unlike the other periodicals, *Science and Children* is not written for children. Its purpose is to help the teacher keep abreast of scientific progress, to suggest better ways of teaching science, and to inform him about new instructional materials in the sciences. *Science and Children* has published numerous articles of theoretical as well as practical importance in elementary science. The September 1965 issue, for example, contains two excellent papers, the first on successful discovery procedures with culturally deprived children, the second on the relevance of modern learning theory to science education. Articles on such topics as wave theory, measurement experiments, conservation, a classroom greenhouse, elementary biophysics, and bird migration are included, along with a brief report by the Council for Elementary Science International and reviews of elementary-science trade books and filmstrips.

Each of these journals is contributing to improved teaching in elementary science and should be available in the classroom. *Nature and Science*, because of its unique qualities, should be purchased in sufficient quantity so that each intermediate- and upper-grade child has his own copy. Whether or not any use is made of it in the classroom, children will enjoy reading it for themselves.

Encyclopedias and dictionaries

The usefulness of an encyclopedia in Inquiry teaching is limited because its editors cannot possibly anticipate all the information needs of children and teachers. Within the restrictions imposed by staff resources and available space, it provides reasonably accurate and up-to-date summaries of information on many topics. Unlike encyclopedias written for adults, the children's encyclopedia is not intended to probe deeply into either the theoretical or the practical aspects of the phenomena discussed. In order to obtain a more complete treatment of any one topic, it is often necessary for children to refer to more than one volume. For example, in the *Young People's Science Encyclopedia*,[22] which is issued in twenty volumes including a special index and study guide, the heading "Frog" in the index gives twenty references to eleven different volumes.

The *Young People's Science Encyclopedia* is a desirable addition to the school library, although it is probably not an absolute necessity. The library which is well stocked with up-to-date children's trade books can satisfy most, if not all, of the demands for science information. On the other hand, if these books are not available, this encyclopedia will help to fill the gap. One of its features is the more than two hundred experiments and "Things to Do" scattered throughout the text. Despite the editorial acceptance of discovery learning, many of these experiments are merely verifying activities which are imperfectly outlined.[23]

Other science encyclopedias for young people are not geared to elementary school children. They suffer from the unavoidable defect of encyclopedias in that children must turn to more than one volume in order to answer any one of their questions. They are useful as supplements, for enrichment and casual browsing, but their purchase for an elementary school classroom is questionable.

The *Compton's Illustrated Science Dictionary* is worthy of mention, because it is the only science dictionary of its kind for children. Most of the definitions appear to be worded for the junior high school children, but it should be useful in the elementary classroom. The incorporation of brief, accurate definitions into one volume increases its ease of handling and frequency of use. Most of the words encountered in the study of elementary science are defined in its more than six hundred pages. The center part of each page is devoted to diagrams and drawings, which elucidate some of the definitions on that page.

Summary

Trade books are one of the most valuable and indispensable tools of elementary science instruction. Their almost endless diversity and richness extend the child's learning horizons, whether he is in the first or the eighth grade. Many trade books are easily utilized in Inquiry teaching, because their content is relatively circumscribed and detailed, accurate and interesting. Children can never perform enough experiments and make enough observations to gather all the facts and ideas that they need; they must turn to such sources as books for this knowledge. Unfortunately, trade books vary widely in quality, and the teacher or school librarian should evaluate them carefully according to such criteria as accuracy, quality and pertinence of illustrations, originality, attractiveness, and the author's qualifications. Sources such as the *Children's Catalog*, the *Horn Book*, *Natural History*, *Science Books*, and the *Library Journal* are most helpful in making these judgments.

Excellent science periodicals, such as *Nature and Science* and the *Cornell Science Leaflet*, are also published for children. They are provocative, accurate, and well written, and should be on hand in every intermediate and upper elementary classroom.

The potential of trade books for enhancing science teaching in the elementary schools has barely been explored. The very fact that they are not textbooks and cannot be used as textbooks is a point in their favor. But, most important, they are flexible, informative, and stimulating. They lend additional strength to science teaching by Inquiry.

For further study

1. Review two books in each of the four classes of trade books—direct experience, information, biography, and science fiction—according to their potential for Inquiry instruction.

2. Choose one scheme from each area of science, and list several appropriate trade books that will enrich the study of each. What are their strengths and weaknesses for this particular purpose?

3. Contrast reviews of the same book in the *Horn Book, Library Journal, Natural History*, the *Children's Catalog*, and *Science Books*.

4. Show how children's periodicals such as *Nature and Science* and the *Cornell Science Leaflet* fit into Inquiry instruction.

5. Write a critique of one of the elementary science encyclopedias or dictionaries with reference to its adequacy in helping you find out:
   (a) Why the sky is blue.
   (b) Why sidewalks crack.
   (c) Why ocean liners float.
   (d) Why some birds migrate and others are year-round residents.

6. Analyze the reading level of a trade book by means of one of the reading level formulas. Is its reading level compatible with that suggested by the publisher?

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17. Zim, Herbert, *What's Inside of Animals?* (New York: William Morrow and Co., 1953), *What's Inside of Plants?* (New York: William Morrow and Co., 1952), and *What's Inside of Me?* (New York: William Morrow and Co., 1952).

18. *Young People's Science Encyclopedia*, 20 volumes (Chicago: Childrens Press, 1963).

19. *Nature and Science*, published for the American Museum of Natural History (Garden City: Natural History Press). $4.50/year for 18 issues of the teacher's edition.

20. *Cornell Science Leaflet* (Ithaca: Cornell University). $1.00/year for 4 issues.

21. *Science and Children* (Washington, D.C.: National Science Teacher's Association). $4.00/year for 8 issues.

22. See n. 18.

23. *Young People's Science Encyclopedia*, Vol. 20, pp. 15–22.

The abundance and variety of contemporary educational materials is probably the most striking difference between past and present science teaching. Audiovisual aids are among the most familiar of these devices. Where once the teacher was singularly blessed if his room contained a blackboard, a globe of the earth, and a map of the United States, teachers are now surrounded by a superabundance of teaching materials, ranging from slide projectors and television receivers to nearby film libraries. If material possessions mean superior teaching, modern instruction is truly superlative. Yet each new device which is introduced into the classroom for the worthy purpose of increasing learning efficiency simultaneously complicates still further the tasks of teaching and learning. This chapter therefore considers critically the problems of audiovisual instruction and suggests evaluative criteria so that the best selection from the multitude of teaching materials may be made. For the purposes of this book, audiovisual aids are defined as filmstrips, slides, motion pictures, television screens, sound records, charts, posters, diagrams, flannel boards, and transparencies.

For commercial reasons, audiovisual materials are usually designed for more than one purpose. They may be motivational, inspirational, factual, reinforcing, questioning, summarizing, aesthetic, historical, probing; they may be intended to replace the classroom teacher, to substitute occasionally for the teacher, or to assist the teacher. No single audiovisual aid is appropriate for all conditions or for all purposes. A film which is right for one fifth grade may be completely useless, even detrimental, in another.

9

Tools of teaching—audiovisual aids

Audiovisual aids are vicarious means of instruction. They interpose an additional level of abstraction on children, who must relate an image on a screen or some other representation of "reality" to a reality which they have never known. Instead of reading about something, they are *seeing* about something. This characteristic of audiovisual aids should be kept in mind as this chapter is studied.

Function of audiovisual aids

The nature of science instruction is such that much of its content is abstract and highly conceptualized, yet concrete materials for young children are essential for psychological reasons. Children have not yet built the internally verbalized structures which allow them to handle reality symbolically and to use the Piagetian formal logic for abstract thinking. Educators strive for abstraction, because of the obvious freedom and power which this capacity gives to children. The case for concrete materials in learning is not limited to young children, however, because even adults fail to grasp such abstractions as the atom unless they have some framework derived from physical experience with the world.

Therefore, one of the most important reasons for utilizing audiovisual materials in elementary school instruction is to help the children deal with content which is not directly at hand. It is, in part, a substitute for direct experience. The film is without peer in bringing into the classroom experiences which are out of the direct grasp of children. Film strips and slides have much of the same power. What, for example, does a child know about volcanoes, if he has only heard of their destructiveness, studied the simplified diagrams of his textbook, or looked at a photograph of an eruption? Although learning from diagrams and photographs in textbooks is probably more meaningful than that which comes out of purely verbal description, the motion picture can vividly portray sequential changes in volcanic activity, bombs of volcanic matter hurled through the air, bubbling lava on the volcano floor, and molten lava oozing slowly down the mountain side. This capacity to convey the power and the awesome beauty of the volcano is unmatched by a textbook.

Another value of audiovisual aids lies in their power to create visually explanatory models of scientific phenomena. Animated films may result in a visualization of molecular activity in gases, solids, and liquids that is far superior to that provided by mechanical models. Indeed, the ability to depict motion when motion is necessary for understanding is one of the great strengths of the motion picture film and of television.

Some audiovisual aids may be strongly motivating; that is, the impact of their careful planning, direction, story line, photography, and content may be such that children are spurred on to learn more about what they have so vividly seen. There is no substantial evidence that this outcome, often postulated for audiovisual aids and especially for motion pictures, is achieved, but this may be because films are often improperly presented in the classroom. It may also be because children have not been conditioned to respond actively. There is a tendency for viewers to settle back, to relax, and to shift quickly from high gear to neutral when the room is darkened. The nagging thought recurs that audiovisual aids produce "a passive person waiting for some sort of curtain to go up to arouse him."[1]

Audiovisual aids may also serve to reinforce previous learning; for example, questions for class discussion may be projected via cellulose acetate transparencies by an overhead projector, or an evocative photograph may be made clearly visible to all with an opaque projector. As the teacher analyzes children's responses to the questions and situations which are projected, both teacher and children benefit from the evaluative strength of audiovisual aids. Audiovisual aids may also summarize, reinforce, and connect the threads of classroom discourse. The bulletin board often fulfills this role, as the children outline on it the important concepts and conceptual schemes with which they have dealt.

One precaution is mandatory. Beforehand, the teacher *must* identify to himself and perhaps to the children, his reasons for bringing in each aid, and then use it for these purposes. He may be forced to alter his plan of attack as a result of unforeseen circumstances, but unless each aid is potent enough to lead to at least *one* desirable outcome, it is not worth the class's time.

Value for Inquiry teaching

As a general rule, audiovisual aids in Inquiry teaching must be functional. As Chapter 4 suggests, most classroom activities in Inquiry teaching should be investigative, centered on direct, concrete learning situations, because it is from these experiences that desirable concepts and conceptual relationships ordinarily grow. However, firsthand experience cannot provide the only path for learning; because of the nature of the self-contained classroom, learning must be somewhat vicarious. Learning which is not firsthand is necessary as children mature, in order to ensure maximum growth in ability to function independently and efficiently.

Therefore, even in Inquiry teaching, films are especially valuable for elucidating conceptual structures. For example, visualization of electron flow in a wire is much improved by animated films which purport to show electrons flowing. The electron is, of course, a scientific construct (abstraction); no matter how glibly children may use this term, it is doubtful that they think of it as anything more than a bit of charged matter too small to see, or that they think of an electric current as more than a flow of these particles through a hollow tube of wire, much like water flowing through a pipe. The representation of electron movement in a number of elementary films provides a simplified basis for raising understanding to a higher level, providing that the teacher simultaneously points out that what is seen is a theoretical model of electron flow. The proper time to present a film of this kind is after an investigation of electric current in wires, when explanations are sought for the differences in flow caused by such variables as wire composition, diameter, potential difference of the dry cells, and resistance. Purely verbal explanations of electron flow, by either the teacher or the textbook, are likely to remain verbalisms; the visualization provided by animation in these films is an effective antidote to symbolic oratory.

Audiovisual aids are often excellent sources to which to turn in order to obtain information for Inquiry purposes. Of course, this role does not rule them out for arousing student interest or for proposing new directions of study. The obligation to reinforce previous learning will also continue to exist, because Inquiry does not mean that drill, review, and testing are to be abandoned. The application of instructional materials to testing is singularly apropos. As a case in point, a filmstrip picturing some of the common lawn or woodland plant groups may be presented at the conclusion of a study of plant inter-relationships. Questioning by the teacher will soon reveal how well children are able to apply their newly acquired knowledge in describing and interpreting what they observe.

Some of the new films and filmstrips include experiments, observations, or field experiences which are not feasible for the class. These experiences should lead to new understanding and new conceptual organizations which are impossible to achieve without these experiences. Lack of equipment or of special facilities is no longer a valid apology for the textbook study of the winter adaptations of animals, the characteristics of the reptiles, or the connection between air masses and weather changes.

In short, audiovisual aids are valuable in Inquiry teaching for much the same reasons proposed for texts, trade books, and other educational resources. They are reference sources from which the data for formulating or for corroborating hypotheses are gathered. But, as we have implied, they are not limited to this role alone. The following critical analysis of the different kinds of audiovisual aids will probe their assets and liabilities in some detail.

Motion pictures

Films have traditionally been the dominant avenue for audiovisual enrichment. Most schools own at least one 16-millimeter projector; many, however, are without proper facilities for projection—a room which may be darkened, convenient electric outlets, and a ready supply of carefully chosen films. These handicaps are greater in large city schools than in suburban or rural schools, perhaps because many urban schools are hopelessly antiquated. Modern projectors are simple to operate, relatively invulnerable to abuse by inexperienced operators, and powerful enough to overcome imperfect darkening.

Any resource which increases the effectiveness of concept formation is desirable, so that time is not wasted with meaningless words. Films are essential for building many abstract, non-experience-centered ideas of space, time, growth, and sequence. They are invaluable for depicting change and motion, and for explanatory animation. Even with their two-dimensional approximation of reality, the success of films in presenting otherwise inaccessible experience is unsurpassed. The semi-direct encounter with processes which are difficult to visualize has been briefly described. But consider, for example, the difficulty of creating a visual image, from experiment or from reading, of a phenomenon such as plant growth, which is magnificently portrayed by time-lapse photography. In minutes, the plants germinate and mature. Children can thus observe by themselves the differential growth of each plant structure, the circumnutatory movements of pea tendrils, and the maturation of the flowers. Of course it is possible and most desirable for elementary classes to study the growth of living plants and animals at firsthand. It is almost impossible, however, for all children to observe each stage as it occurs. Therefore, the joy and excitement which comes as the Monarch butterfly emerges from its chrysalis is denied them unless it is brought into the classroom on film. Even the static succession of developmental steps which slides or filmstrips offer is preferable to a drawing in the textbook.

In studying the adaptations of birds to their environment, a close examination of wing movements for taking off, for flying, for obtaining food, diving, slowing down, and landing is hardly practical without motion pictures. The revolution of the planets around the sun, the moon around the earth, and the motion of the solar system through space is beautifully visualized on film. Children find it difficult to conceptualize these complicated movements, because of their limited understanding of mechanical forces.

The direct entrée of experts into the classroom via the motion picture is still another source of assistance to the teacher. The expert, a man who intimately knows his field, may present important ideas and questions in a challenging and provocative fashion. He may perform a difficult demonstration, provide new data, and direct attention to significant events.

One of the best uses of films in the upper grades is to bring to the children experiments and demonstrations which are ordinarily impractical in the classroom. The expert demonstrator, fortified by ample time and experience, can elucidate, in the course of a few minutes, phenomena which are too difficult or too dependent on specialized equipment for most schools. For example, much that we know of atomic structure is derived from the radioactive decomposition of certain atoms. Children have heard of Geiger counters and of alpha particles. In the course of a unit on the atom in the upper elementary grades, they will meet these phrases in their reading. Suitable demonstration equipment for the purpose of matching the words with their scientific meanings is not often available in schools. Films which illustrate Geiger counters and explain their operation, with or without their far-reaching scientific implications, substitute for firsthand experience. Such films, if carefully selected, are better by far than an inferior classroom demonstration. Their educational value depends on how well they are used—on their quality, on the degree to which children are prepared to profit from them, and on the skill with which the teacher relates the facts and concepts presented to the problems of concern to the class.

Commercial narration is often a bland, syrupy concoction, which in its headlong struggle to describe everything describes nothing. Films whose narration is disturbing may be excellent if the sound is turned off and replaced with a teacher-directed commentary. There are relatively few times when a film's sound track needs to be heard. Such occasions (e.g., bird song, study of sound itself) are obvious. The teacher may thus emphasize those parts of the film which are most significant; she may also raise questions for future discussion. The film may even be shown in slow motion, and frequently halted for discussion.

Films are sometimes used to teach the tactics of Inquiry. Richard Suchman, formerly at the University of Illinois, has prepared a series of films each of which silently demonstrates one scientific principle in the course of a few minutes.[2] Following exposure to each film, elementary school classes attempt to elucidate the pertinent principle by a series of questions to the teacher. The children narrow the scope of their inquiry, eliminating irrelevant ideas and conditions, and finally learn to focus on the relevant elements of the demonstration. Such a film is useful for this purpose because children are not distracted by the side effects of classroom experimentation nor by inability to see precisely what happens. In every case, however, the demonstration can be carried out in the classroom exactly as shown in the film.

Proper use of films

It is axiomatic that films should be chosen carefully. Thousands of films are listed in the various catalogs; their brief annotations are invariably insufficient to provide the complete information desired. The teacher who uses motion pictures wisely should not rely exclusively on the advice which the Director of Audiovisual Aids in his school system is happy to give. No matter how competent the Director is, the teacher cannot delegate his own responsibility, because *he* knows the children for whom the film is intended. It will help him to consult a list of time-tested, popular films, in order to eliminate those which are obviously unsatisfactory. Since film guides do not generally classify films according to their most suitable uses, teachers must preview the films and, no matter what the financial sacrifice to the school, refrain from using them unless they are exactly right. Films usually cost several dollars a day if it is necessary to rent them. The cost in time wasted, in disappointment, and in disillusionment is much too great to justify the showing of inappropriate motion pictures. Because the teacher should screen the film prior to use, it should arrive at least a day before the planned showing. The criteria which are given below will assist teachers in assessing the strengths and weaknesses of motion pictures:

Criteria for film evaluation

1. What can the film do that the teacher and his class cannot do as well or better?
2. Does the film waste time on exposition of extraneous ideas and activities?
3. Is it competently produced? Is it sharp and clear?
4. Is it up-to-date? Is it accurate? Are the consultants or advisors listed in the credits scientists?
5. Is the class prepared to see it? Will the children profit from it?
6. Is the film likely to stimulate activity? Will it motivate the class to make use of the ideas in some constructive way?
7. Is a simpler audiovisual aid, a filmstrip for example, more likely to be useful?
8. Is the film worth the time and effort to use it properly?

Research on motion pictures has led to many important guidelines for proper utilization. For example, children obviously like to watch films, but the interest which they show is no guarantee that they learn more effectively. Learning is dependent on the design of the film and on the way it is used in the classroom. A sleek color film embellished with melodious musical accompaniment may result in diminished learning, because color and music are distracting. Humor, despite its appeal, distracts. Attention is diverted from the important task at hand by these irrelevancies.

Most films do not amplify important ideas sufficiently. They move too rapidly for children, and their brief summaries are therefore meaningless. It is now well known that two showings are more productive than one; three, however, are not *necessarily* better than two. From a psychological point of view, repetition is important for the less able student; the academically superior child also profits. This does not mean that the two film runs must be carried out in exactly the same way. If the film was first presented with its accompanying narration, it may be rerun in slow motion with teacher commentary.

Learning from films is enhanced by directing the class to significant portions, either by direct comment, by pretesting, or by some other attention-focusing device. These techniques are especially valuable prior to the second run, because children will then have a frame of reference into which the second viewing may be assimilated.[3]

Films should incorporate many clear labels and pointers to identify important structures or processes. Their effectiveness is also heightened if they include questions and allow enough time for children to read or listen to the questions and answer them at once. Questions at the end of each segment of the film are more effective than introductory questions, although the latter may direct attention or help motivate children. Teachers may also ask questions of their own.

Teachers often feel obligated to show the entire film, no matter what its length. It is often desirable, however, to show only a pertinent portion, which may be accomplished by advance planning. Only a few minutes of many films are profitable. The teacher must not yield to the inevitable demands by her children to see all of the film. Motion pictures in elementary science are not entertainment; they are tools for learning, to be used to accomplish a specific purpose.

One of the most promising of modern developments for overcoming the problem of excessive length is the film loop, which is a short, three- to five-minute continuously running film. It deals with one major idea or process, and, because of its continuity and repetition, is an astonishingly useful device for special purposes. The number of film loops suitable for elementary-science instruction is increasing rapidly, because of their low cost, convenient manipulation, and inherent worth. (See Chapter 10, p. 327.)

Above all, when using motion pictures, the teacher must strive constantly to shake children out of the inertia with which they customarily watch the screen. He must, by every device at his command, force children to interact vigorously with the stream of words and images which is projected at them. Unless he succeeds, the class will be entertained, but it will not learn.

Problems in the use of films

Few schools possess a film library with enough prints for meaningful choice. Ordinarily, films must be booked weeks or months in advance from a commercial film library. Because they are available for only a day or two, previewing is sometimes omitted. Scheduling so far ahead is undesirable because it structures the curriculum around films. If, for example, the only free date for a film on beavers is March twenty-second, then March twenty-second inevitably becomes the target day for a probe into the ecological adaptations of beavers. This is a perversion of curriculum planning, because convenience takes precedence over rational ends. The film must be shown at an inconvenient time or else its genuine values must be surrendered in favor of a more readily available but less desirable substitute. These disadvantages may be overcome by ordering films for a longer time. A film costing three dollars for one or two days may not cost more than five dollars for the full school week. With this extended time, the film may be exploited. The added cost, however, and the increased competition with other schools, which arise from scheduling a number of films for more than one day, add to the difficulties of ordering films.

Many schools have not yet made it easy for teachers to use films. It is not unusual to find rooms insufficiently darkened, mechanically inadequate projectors, untrained operators (although the newest projectors are almost self-operating), and an inordinate amount of time wasted in threading and rewinding the film. The dogma which equates films with entertainment is responsible for the unpardonable practice of inviting into the classroom unprepared classes of children (and teachers) or of showing the film in the school auditorium to many more children than are ready to profit from it.

Television

Throughout the nation, children are able to watch science lessons on closed- or open-circuit television. Most metropolitan centers, many school systems, and, indeed, entire regions have improved the quality of educational television by means of carefully planned sequences of science programs. Televised science lessons may be strikingly similar to motion picture films, but as they are usually programmed they are a technique for bringing to the child a structured content of secondhand experience. The television teacher, a specialist in science education, is not always an experienced teacher of young children. At its best, however, televised science is superb in its use of every technological resource for effective teaching. For example, the action may move smoothly from a demonstration to explanation by animated cartoon or from a magnet board on which questions and summaries are recorded to a photographic enlargement of the phenomenon being discussed. The possibilities are limitless.

There is little reason to doubt the mesmeric quality of television, because of the conditioning to television which children bring from home. The excellence of television receivers in the schools is continually increasing; screen sizes are larger, and the power and the number of broadcasting outlets is growing daily. Technically, classroom television is more potent than ever before.

The most pertinent objection to teaching elementary science by television is that television, like motion pictures, structures classroom content. Titles and lesson plans for the televised lessons are usually known in advance, so that instruction may keep step. This rigidity is not necessarily disastrous if these lessons are taught by Inquiry techniques for teachers who turn to them only for guidance. Unfortunately, this is not the usual teaching pattern. Science on television is generally a series of demonstrations by a manipulator who merely substitutes for a textbook. There is neither opportunity nor reason for developing Inquiry procedures, nor is there feedback to the television instructor so that he can profit from classroom experience.

This kind of instruction may be preferable to science as it has conventionally been presented in elementary school classrooms throughout the country. Because, however, it ignores the goals of Inquiry, it is sterile. It will take an unusually discerning and skilled teacher to utilize these predigested capsules of science in educationally justifiable ways.

The results of research in televised science instruction are difficult to interpret. Television science taught by heuristic methods, which are aimed at creating an involvement and interaction by children with the science process, is almost non-existent. Children do not seem to learn appreciably less science when judged by retention of facts and scientific principles presented on television, nor do they appear to learn more. There is some evidence that children who are from a higher socioeconomic level or are of superior intelligence are *less* stimulated by televised science to form positive attitudes, to develop interest in finding out for themselves, and to make the desired shift from extrinsic to intrinsic motives.

If science is to be taught in conventional ways, if the major goal is learning of facts and principles as judged by achievement on standardized tests, then educational television, like films, has a contribution to make, because of its capacity for enriching instruction. Television also suffers from most of the drawbacks of motion pictures; instead of the projector bulb burning out in the middle of the lesson, atmospheric conditions or a low-flying airplane may disrupt the image.

Although television science is not designed for discovery teaching, teachers who know the program content in advance may propose problems whose solution rests on data from the television lessons. In this case, television is another source of information, and it is not necessarily the best. In general, Inquiry teaching is unlikely to benefit from televising elementary science. A textbook is not improved because it is reshaped and projected on a 21-inch television screen.

The didactic nature of television science at its best is illustrated by the popular "Mr. Wizard" programs, which are no longer available. Mr. Wizard is a master demonstrator, who creates beautifully simplified explanations of complex scientific phenomena. His aim, to teach understanding of these phenomena, is effectively accomplished. He makes no effort to stimulate children to find out for themselves. It is possible that a child who has become personally involved in the program may bring to the classroom questions which puzzle him, or may come with the desire to try out an interesting demonstration. Mr. Wizard, however, does not directly seek these outcomes; his methodology is that of direct telling.

Television has its advantages, of course. It brings to children the vicarious experience of a whole world. In a superficial sense, it has been instrumental in raising children to greater sophistication. The reality of a rocket launching, the impact of a rocket probe on the moon, an exciting eclipse of the sun—these are the events which, because of their immediacy and emotional content, are uniquely adapted for television. News programs and documentaries add to the educational value of television. With few exceptions, however, elementary school children are almost completely ignored by commercial television in its public-service programming. Educational television has not yet been able to accept its proper responsibility in providing for these children the richness of experience which it promises.

Closed-circuit television in individual school systems frequently rises above the humdrum banality of talking at children. This divergence from the usual model of elementary science instruction occurs when a gifted teacher is joined by an understanding director and producer in working closely with a relatively small group of classroom teachers. It is possible with this arrangement to introduce and maintain the excitement and interest of firsthand exploration in science. Only large school systems possess the necessary resources of staff, time, and money for closed-circuit television. The larger the system, the greater the demand for a carefully sequenced curriculum lockstep. Unfortunately, the kind of science teaching which is advocated in this book is not neatly begun and ended in thirty-minute programmed bundles on Monday, Wednesday, and Friday; within a few days, teachers who practice Inquiry teaching will be hopelessly outdistanced by their television colleagues.

Filmstrips and slides

The full potential of filmstrips and slides has yet to be attained in elementary-science instruction. Hundreds of filmstrips are advertised for sale, in contrast to the handful of slide sets. Slides, despite their advantages, are not often used in either elementary or secondary schools. Filmstrips are inflexibly sequenced collections of visual materials. Although individual frames may be omitted, the order in which images appear is almost impossible to change without physically destroying the filmstrip. If the order is changed by moving back and forth from frame to frame, the result is likely to be a bewildering series of kaleidoscopic images. The best juxtaposition of frames is easily achieved with standard-sized slides, but individual slides are more troublesome to catalog, to store, and to manipulate.

Filmstrips and slides possess many of the advantages of motion pictures and television, and are probably better for most elementary science uses, which do not need motion or animation. They are particularly helpful in those phases of science which are not handled easily and concretely in the classroom – ecological relationships and industrial applications, for example. The low cost of filmstrips, approximately five dollars for forty or fifty frames in color, encourages school ownership and thereby increases the accessibility of filmstrips. Many of the newer filmstrips are accompanied by a detailed syllabus or a recorded narration that is synchronized with each frame in order to provide some guidance. These narrations may handicap good teaching in precisely the same way that motion-picture sound tracks are obstructive. They focus attention on matters which may be of little concern to teacher and class. They may cover too much, move too fast, and lead to confusion rather than clarification. The teacher's own commentary is probably much more suitable for most filmstrips.

Appropriate titles and questions in the filmstrip will help children to attend to the proper points, prepare them for forthcoming ideas, and review previous learning. Whenever desired, the filmstrip may be stopped in order to discuss an individual frame in detail, and it is possible, when helpful, to return to an earlier frame for contrast or for reinforcement of learning.

Teachers should always preview the filmstrip before teaching with it, and, as they move from frame to frame, they should use criteria such as these for evaluation:

Criteria for filmstrip evaluation

1. Is the information more easily obtained from other sources, such as reading, classroom experimentation, field trips, discussion, or films?
2. Is the filmstrip likely to be helpful? Is it within the grasp of the class? Is it clear, both intellectually and photographically?
3. Is it burdened with extraneous material?
4. Will it be available when it is wanted?
5. Is it interesting? Exciting?
6. Will it organize previous knowledge effectively? Does it provide challenging situations to which children's learning may be applied?
7. Is it accurate? Who produced it?

The teacher must decide whether or not the time taken for showing the filmstrip is well spent. Good teaching is often a process of making the right decision. The teacher is confronted at every point of the teaching-learning process with competing pathways for attaining his goals. The master teacher, perhaps intuitively, but more often because of a practiced critical judgment, chooses the right technique – that which is right for him and for his class. The probability of being right is dependent on understanding of the techniques, their assets, and their liabilities. Therefore, it is unwise for the teacher to rely on secondhand evaluation of even so innocent a teaching aid as a filmstrip.

One of the chief virtues of slides, despite their infrequent use in the classroom, is that individuals in the community may have useful teaching collections on hand. The teacher who, in her travels, has taken color slides of the Grand Canyon or of Yellowstone Park is fortunate. Teachers who lack this resource will probably find one or more individuals locally who will lend their collections or will even show the slides themselves, with their own commentary. Although it is probably true that personally owned slides are better adapted for social-science or geography instruction, teachers ought not neglect the possibility of other people's slides for science instruction, because of their inherent flexibility and interest.

Transparencies

The transparency is one of the newer audiovisual aids. Commercial sets of transparencies designed for elementary-science instruction are available today. These transparencies, reproduced on sheets of acetate film, are projected on a screen by an overhead projector. They are clearly visible even in a well-illuminated room, and are a major resource for classroom instruction. Commercial transparencies are most often produced for the upper elementary grades or for high schools. Each prepared sheet costs several dollars or more. The more expensive transparencies include overlays, sheets which are folded over a base film in order to introduce new structures, concepts, explanations, or questions, in a predetermined sequence. Transparencies tend to be limited to diagrammatic representations or drawings, although actual photographs are sometimes used.

Transparencies are conveniently thought of as substitutes for writing and drawing on the blackboard. The teacher faces the class as the transparency is projected, so that he may speak directly to the children as they look at the magnified image on the screen. The time-honored but inferior technique of pointing to a picture in the textbook or to a picture or chart hung in the front of the room which is invisible to most children is therefore unnecessary.

Overhead projection is clearly destined to be an ever more important educational tool, even though there are few commercially produced transparencies on the market today which are worth their price. Their potential for clarifying individual points, such as the relationship of body organs, which are visualized by a series of overlays, for review, and for drill is almost unexplored. Many school systems now own the necessary devices for reproducing photographs and diagrams and for creating black-and-white or color transparencies. Thus teachers are not restricted to commercially prepared materials but are free to select from an infinite variety of sources those illustrations or diagrams which are pertinent and which, within minutes, can become useful audiovisual aids. However, production of color transparencies and overlays is more time-consuming than simple copying in black-and-white.

In general, overhead projection of transparencies is one more technique for supplying resource information to children. No audiovisual aid is a panacea for solving all the problems of teaching. But relationships of structures must be analyzed, and when the teacher wishes to summarize material or identify some structural feature or characteristic, he should consider carefully the possibility of utilizing transparencies.

The chalkboard

The chalkboard ought not to be ignored in the multitude of audiovisual devices now available, if only because it *is* present in every school room. Chalkboards have no moving parts to burn out or to break. It is possible to draw or write on it in letters so large that every child can read the ideas, concepts, and summaries which are presented to them. In the course of a lesson, the teacher or the class secretary can create a visible record of the important points. Science may be taught without a chalkboard, but the chalkboard is unsurpassed in its operational simplicity.

Unfortunately, drawings and words can remain on the board for only a short time. Detailed drawings consume time and are all too quickly erased. Important drawings should either be reproduced for class use or be copied by the children. Since chalkboards are usually designed for the teacher, children are often unable to use them, because they are too short to reach the entire board.

Flannel board

The flannel board serves many similar functions. It is particularly suitable for the "What We Learned about Air Pressure" kind of display, in which cut-out letters, drawings, and diagrams are mounted for an extended period. The flannel board is also useful in discussions of those phases of science which involve changes of position or relativity of position. The figure of Mr. O, the outside observer invented by Dr. Robert Karplus, may be quickly moved from position to position in order to illustrate how the observer's point of view changes with physical orientation.[4] (See pp. 199–202.) In the study of planetary motions, the relative distances of the planets from the sun at perihelion and aphelion may be readily illustrated on the flannel board. Because the flannel board is a simple, sturdy device, and because it provides one more aid for better learning, it should be available in every elementary school classroom.

The bulletin board

The bulletin board tends to be a static, rather inflexible teaching tool. All too often, its main function is to exhibit the "finished" work of the class to visitors. There are many other functions for which it is appropriate. It may help to generate interest or to focus interest on some phase of instruction. For example, the teacher who plans to introduce his class to the gravitational interactions of our solar system may set up a display of photographs of the members of the solar system from such sources as *Life* or the *National Geographic*. These photographs may be given such captions as "What Keeps the Planets Moving?" and "Why Does the Earth Move around the Sun?"

As the class begins its study, the display may be changed with each phase. The earth-moon system may be represented by means of scale drawings of the earth and moon as the moon moves around the earth. Labeled arrows can explain how gravitational forces hold the moon in its relatively circular orbit around the earth. Questions such as the following draw attention to important concepts: "Why doesn't the moon fly off into space? How do man-made satellites resemble the moon? Why doesn't the moon fall to earth? How long does it take the moon to move all the way around the earth?"

Results of "research" problems are well adapted for bulletin board display. Each group of "researchers" should plan an effective exhibition, for which children with artistic ability will provide the leadership. The need to fit their discoveries and conclusions into a minimum space with maximum narrative power will challenge each group.

The usefulness of the bulletin board for summarizing both long- and short-term activities should be noted. The important concepts, principles, and laws which the class encounters will, if recorded on the board, serve to remind the children of what they have learned. These ideas provide a nucleus for review and synthesis in the culminating phases of classroom investigation.

The bulletin board is not a major ally of the teacher who is concerned with Inquiry. It makes no unique contribution in fostering children's ability to think scientifically. Its limitations of space, however, should force children to express their ideas briefly and cogently. It is the degree to which this function is achieved that entitles the bulletin board to a place in modern science instruction. Effective bulletin board displays are carefully designed to combine economy of content with clarity of meaning. Drawings, photographs, and captions should be selected for the contribution which each makes to the total effect. Colored string joining bright captions with vivid illustrations enhances visibility and relationships. Excessive color may produce a garish, self-defeating jumble. Artistic excess must be subordinated to scientific accuracy. Plant drawings or cut-outs are much more effective if in natural color. On the other hand, colored circles purporting to represent gas molecules are meaningless because colored gas molecules are meaningless. Children may misconstrue "colored" molecules, even though they are colored in order to enhance visibility. In every case, the teacher should endeavor to portray nature realistically, and she should weigh carefully the comparative advantages and disadvantages of color on the bulletin board.

Records and tapes

At present, phonograph records and tapes offer little of value for Inquiry teaching, partly because few records and tapes have been prepared for elementary science. There are some recordings of songs written especially for science, which purport to teach such assorted facts and concepts as magnetic interaction, the water cycle, and the simple machines. It is difficult to justify the cost of such records for a school. They may arouse interest in younger children, although this is somewhat conjectural. The attempt to correlate science with music is a far-fetched extension of the Herbartian correlation of the elementary school subjects. Science songs are sugar-coated doses of facts and principles; if they have a function, it is to encourage the painless learning of information for the music's sake. Teachers may find some opportunity to introduce science songs in the summarizing activities which she and her class plan. They *are* enjoyable, and harmless when so used. With this exception, their place in elementary science instruction is questionable.

One major exception to the general unsuitability of records in elementary-science teaching is in the investigation of sound phenomena. It is possible to purchase records which illustrate the Doppler effect, musical overtones, and pitch-frequency relationships. Some of these sound effects are not easily produced in the classroom, and this kind of recording is therefore a valuable classroom aid. Excellent recordings of animal sounds—insects, birds, mammals, and fish—will add still another dimension to the study of the living world. One set of these records is probably all that is necessary in most schools.

Science information recorded on records or on tape all too often exemplifies the product aspect of science. The records which are available are fact-centered. They suffer even more from the disabilities of motion picture sound narration, because they are not integrated with a visual image.

Teachers, however, are not confined to commercially prepared auditory aids. A number of teachers have taped classroom discussions and student reports which, replayed at leisure, facilitate an analysis in depth of the classroom dialogue. Teachers are able to evaluate their own contributions, their impromptu decisions, and the blind alleys which sometimes confront them; at the same time, they are free to listen to and to analyze each child's participation better than ever before. By replaying the tape to the class, the teacher may begin a cooperative examination of the relevance of class hypotheses, their assumptions and erroneous conclusions, and their general strategy in attacking problems. (See p. 362.) Dr. Richard Suchman has clearly demonstrated the improvement which children with this kind of training show in problem solving.[5]

Opaque projection

At one time scorned as a trivial gadget, the opaque projector has established a legitimate role in audiovisual instruction. The ease with which a picture or diagram may be projected directly from a book or periodical is a substantial point in its favor. Without special equipment to transfer the picture to a transparency, the opaque projector is often the only device by which an enlarged image may be screened. Few classrooms have an opaque projector on hand, ready at a moment's notice, however. Therefore, it is hardly worth the effort to requisition the projector, to put out the lights, and to draw the dark-curtains in order to show one or two insignificant illustrations. Teachers who use the opaque projector effectively select illustrations which are stimulating, help to explain pertinent ideas, or which present information most economically. The magnificent photographs of the Moon's surface and the detailed electron-microscope photographs of cells, which have been published in many periodicals, are ideal for opaque projection.

Unfortunately, the extreme room darkening required delays taking notes and postpones the customary teaching techniques for analyzing and summarizing the concepts and relationships presented. The teacher must weigh carefully the relative advantages and disadvantages of opaque projection. If he believes that the class will profit from opaque projection, this should be sufficient. If more convenient and simpler means will achieve the same ends, he should not hesitate to leave the opaque projector for some other time and duty.

Models

In direct contrast with some audiovisual aids, material for making models in elementary science is plentiful. The authors define a model as a more or less faithful copy of some physical structure. For example, models of human anatomy, plant leaves, motors, and rockets are available; they vary in detail and accuracy. Some models, such as motors, may actually operate like their prototypes. The function of most models is to facilitate examination of structural detail and of the functional relationship of parts.

Costs and values of commercial models vary widely. A model of a human torso may be surprisingly exciting to a class of children because of its direct representation of the body organs and their relative sizes and spatial relationships. Its cost, however, may be prohibitively high. A tellurian is helpful in simplifying the complex motions of the moon and earth around the sun. The advantages of more or less realistic three-dimensional physical replicas are real and numerous, but sturdy models are expensive. If they are simplified, either to reduce cost or to eliminate unwanted detail, they may become meaningless. Leaf models are often so generalized that their resemblance to actual leaves is negligible. Erroneous ideas may easily be formed by overreliance on such models. The tellurian, for example, may successfully elucidate the movement of the moon around the earth, but its inevitable distortion of scale and velocity is likely to produce new misconceptions.

Inexpensive plastic toy models, usually in kit form, are popular and sometimes instructive, but they are generally too small to be demonstrated effectively. Models of many common animals and plants are stocked in neighborhood stores. The assembling of kits is worthwhile if it helps children to understand the prototype's structure, the relationship of its parts, and its mode of operation. The difficulties in achieving conceptual growth by model building are well illustrated by the meager intellectual outcomes of model airplane construction. Most boys are able to put together a reasonably well built model. It may even bear a decided resemblance to the airplane which it copies. Few boys, however, learn from this experience how an airplane flies, how the rudder and elevators function, and why the airplane is able to defy the "law of gravity." Teachers must pursue the "why and how" instead of the "what"; models, if unwisely employed, restrict learning to the "what."

Obviously, the model should be realistic; if it works, it should work realistically. Simulated operation poses a formidable instructional hurdle. For example, one of the activities that culminates the study of earth changes in many schools is the construction of a plaster-of-paris volcano, whose eruption is simulated by the decomposition of ammonium dichromate. In a semi-darkened room, the model seems quite realistic. Lava belches forth; sparks flash from the crater, accompanied by clouds and an impressive hissing. Unfortunately, real volcanoes are not charged with ammonium dichromate, nor is their lava green, and as a result the model may be deceptive and, from the standpoint of safety, somewhat hazardous.

In assessing models, teachers should consider visibility and accuracy of detail. The questions listed below will assist teachers to evaluate the potential of models in science instruction:

Criteria for Evaluating Models

1. Are the important parts clearly visible?
2. If it is a working model, does it work like the prototype? If operation is simulated, will it be necessary to explain the processes which the children should understand?
3. Is the model faithful in scale and appearance to the prototype?
4. How durable is it?
5. Are transparencies, photographs, or charts effective substitutes?
6. If construction is necessary, will the physical act of fitting the pieces together promote learning?
7. If the model is commercially produced, is it worth the expense?

The diorama

The diorama is a two-dimensional painting on a large scale or a three-dimensional composition which joins a painted background to various objects and structures in some kind of natural relationship. A diorama portraying a river valley may be valuable in clarifying erosional processes. A diorama of the dinosaur life which flourished during the Cretaceous period may be an interesting way to summarize the study of prehistoric plant and animal life. The diorama is another construction activity which involves numbers of children; because it requires physical activity, it will be enjoyable; because its outcome is tangible, it is easily evaluated; and because it is dramatic and clearly shows how hard its creators have labored, it makes for good public relations.

However, the usual words of caution must be reiterated. Construction by itself and for itself serves no useful purpose in science. If, however, in planning and building the diorama, children grow in their ability to plan and to work together, if they derive the data they need by themselves in educationally sound ways, they will have taken a positive step in their education. The project for its own sake is discredited. Learning does not automatically emerge from physical activity. It is perfectly possible for children to escape from a unit on erosion with no real understanding of erosional forces and the time scale in which erosion occurs, despite extensive model building and diorama construction.

Summary

Elementary school science is in an ideal position to capitalize on the flood of old and new audiovisual aids now on the market. The possibilities of enriching and broadening learning more efficiently and more economically than ever before are within the grasp of most elementary schools. Effective learning is contingent on many interactions with the physical and intellectual environment of the child. It is frequently impossible to bring into the school the direct experiences which ideally make for good science instruction. Audiovisual aids such as motion pictures, slides, filmstrips, television, opaque projection, and models may, if wisely utilized, provide many of the vicarious experiences which catalyze learning. Audiovisual aids are convenient and effective ways of motivating children to study fields of science of which they have no experience. They help the teacher to organize his teaching so that a minimum of time is wasted in summing up and clarifying important ideas, in reviewing, and in drilling.

Before each audiovisual presentation, the teacher must question the value of the aid he plans to use. Will it do what he wants? Is a motion picture better than a filmstrip? Will a model so enhance learning that its cost is immaterial? Will there be time to preview the film or filmstrip in order to take full advantage of it? Unless the answers to these questions are strongly positive, it may be much the wiser course to rely on such simple devices as bulletin boards, transparencies, and chalkboards. Time, the teacher's and the children's, is too precious to waste in superficial and trivial instruction.

Such possible disadvantages as the conditioning of children to passive behavior, mechanical difficulties with apparatus, room-scheduling, and room-darkening must be carefully considered. It is possible to schedule a program of science instruction around a motion picture, but this kind of science instruction will not produce active, inquiry-centered children with a taste and the intellectual strength for coming to grips with modern science learning. Wisdom and judgment in selecting the right audiovisual aid will come with experience and practice. Audiovisual aids *are* aids. They will neither replace the teacher, nor cause extraordinary growth in learning. They will, however, help the teacher to present to his children the whole wide world of science more efficiently and more dynamically.

For further study

1. Is the objection that motion pictures foster passive learning valid?
2. To what extent is the availability of audiovisual materials a determining factor in structuring science instruction in the elementary grades?
3. Write a critique of an elementary science program that is televised by an educational television station.

4. Make a close study of science motion pictures for primary-grade children and for intermediate-grade children in each of these categories: (a) physical science; (b) biology; (c) earth science. Repeat the analysis for filmstrips, science records, and a set of transparencies for overhead projection.

5. How can photocopying machines improve audiovisual instructional techniques?

6. What are some of the reasons for the relative failure of sound motion pictures in many classrooms?

7. When is it educationally justifiable to show a motion picture film only once?

8. What are the implications of research studies in which the major contribution to teaching is made with audiovisual aids, and personal participation by a classroom teacher is minimal?

9. Will closed-circuit television strengthen elementary school science?

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10

Tools of teaching—facilities and equipment

Elementary school science can be taught with the crudest of home-made equipment. With the right teacher, it can be taught superbly. The fact remains, however, that most teachers are not geniuses at improvising substitutes for necessary apparatus; they lack the time and tools for construction. If we expect elementary science to be experimentally derived, we will have to see to it that classroom teachers have the necessary equipment and supplies. One of the most heartfelt complaints of the classroom teacher is that he is often expected to teach science without science equipment.[1] Of course, there are teachers who are either incapable of using or unwilling to use supplies and equipment already at hand.[2]

By "*facilities*," the authors mean the classroom itself, along with its storage space, electric outlets, demonstration desk, dark shades, work surfaces, sinks, projection screen, and so forth. "*Equipment*" or "*apparatus*" means the more or less permanent materials for experimentation and demonstration, such as ring stands, lenses, hot plates, and the aneroid barometer. "*Supplies*" are the materials which are used up in the course of time, or which are fragile and therefore frequently replaced. Chemicals, test tubes, balloons, and iron filings are examples.

Few elementary experiments are so complicated that they cannot be performed with improvised or substitute equipment, particularly if the teacher or child is knowledgeable. If construction of a piece of apparatus helps the child to understand fundamental principles better, construction is clearly of value, but the teacher must carefully weigh this value against the demands of time. If little of scientific value is to be gained by construction, a commercially manufactured piece may be much better. For instance, children can assemble a crude galvanometer which will respond to an electric current and which can be used in a number of simple experiments. The operation of this home-made galvanometer, because of its open construction, is somewhat easier to understand than the operation of commercially manufactured instruments. However, this galvanometer is too insensitive for comparative measurement of current flow. It is also possible to build a simple device by which the rate of heat flow through different metals may be compared, but the elegance and simplicity of the conventional heat conductometer negates whatever savings emerge from the home-made apparatus. On the other hand, the learning which comes from *building* a small telescope is far superior to that which comes from *using* a telescope, because the builder-user learns much more about the science of light than does the person who only uses the telescope.

In order to maintain an effective elementary-science program, there should be on hand or quickly available a basic store of equipment and supplies in a room designed to facilitate instruction—one with running water, adequate counter and work space, and good storage.

There are many sources of equipment and supplies for teachers. Most schools expect each teacher to order and to maintain those science materials which are required for his classes. Many school systems employ science supervisors or consultants who are anxious to assist teachers in planning for and in ordering necessary items. They have catalogs and time-tested lists of materials on hand. In addition, the teacher can turn to innumerable publications for help in selecting equipment and supplies. Most elementary school science curriculum guides include detailed equipment and supply lists. Teachers should feel free to call on their colleagues in local junior and senior high schools. Elementary school teachers are often reluctant to "intrude" on high school teachers, fearing that they will be unwelcome. On the contrary, high school teachers are eager to help in every way, but they, in turn, hesitate to force themselves into the elementary schools. Teachers who turn to the high schools will find that they are welcome, and will receive prompt and effective assistance.

Lists of supplies and apparatus, important though they may be, do not provide a final answer to the problem of selecting materials. Lists are compiled for general courses of study, whose emphases and purposes are likely to be markedly different from those of the individual teacher. His needs may not be satisfied by a list taken from the state syllabus. However, wise planning over a period of a few years will stretch a limited budget for supplies and apparatus, and, if there is a science supervisor in the school system, he will provide special items which are beyond the reach of individual teachers, such as a mercurial barometer, vacuum pump, or demonstration steam engine. Children will often add such useful materials as shell and insect collections from home.

The following general criteria for selecting scientific apparatus and supplies will be useful:

Selecting Apparatus and Supplies

1. Is this piece of apparatus functional? Does it perform according to specifications? Is it approved by the *Purchase Guide for Programs in Science and Mathematics*?[3]
2. Is its expense justified by its potential uses?
3. Is it safe?
4. Is it durable, reliable, and uncomplicated? Will it work with a minimum of maintenance? Is repair likely to be expensive and time-wasting? Can it be repaired locally?
5. Will children who sit at the rear of the room be able to see the important details? Is it large enough so that children can manipulate it?
6. Are there less expensive substitutes?
7. Is it a "black box" instrument, whose internal operation is hidden from the class? Is it too advanced, too complex for the class?
8. Is it easy to store?
9. Are operating directions easy to follow?
10. Does it have a potential for many learning experiences, or is it more limited? If it is not versatile, is it indispensable for its intended purpose?

The cost of a piece of scientific equipment is not always a sound guide to its value. Low-cost equipment is often unsatisfactory, but high quality is not guaranteed by high cost, and the elementary-science equipment market has been invaded by a few companies in search of quick profits from shoddy merchandise. Reputable supply houses, such as those listed in the *Purchase Guide*, guarantee their merchandise, and do not mislead the unwary buyer with deceptive advertising.

Science centers and science corners

Teachers who are interested in science often reserve a section of their room for the "Science Corner." This is where children congregate to explore a provocative new exhibit, repeat a demonstration, or work out a science problem for themselves. The science corner is the place where the class pets are kept, the plants are grown, the equipment stored, and the science trade books and periodicals shelved. The science corner has been a fruitful center for science study in many classrooms. Displacement of science facilities from the center of the room has occasionally been criticized as a restrictive device which minimizes the importance of science in the classroom.[4] This criticism is not justified if the science corner is regularly used by the majority of children as their laboratory.

However, the science corner *is* limiting, because only a few children can be accommodated at one time, and the variety and quantity of materials which can be stored there is small. Because the task of teaching science is immeasurably facilitated by special resources, a number of schools have either built or remodeled rooms for elementary-science instruction. The special science room has many uses. It is the place to which teachers take their own classes for science lessons and where groups of children pursue their interests. All of the science materials for the entire school may be stored here, carefully inventoried for convenience. This room is a natural location for in-service science workshops and for inspection and evaluation of new pieces of equipment.

In one school, the science center includes an animal area which is located in a corner near the sink; facilities for aquaria; a plant-growing area in an improvised greenhouse heated by an electric light bulb; a U-shaped demonstration table with accessory shelves and drawers; a weather study area near the windows, equipped with appropriate charts and instruments; a reference area, supplied with trade books, picture collections, and a resource file listing local field trips and consultants; and a storage area for science materials which are not stored elsewhere.[5]

Some schools operate a less elaborate center, from which teachers may draw whatever special pieces are necessary for regular classroom instruction. These centers are usually supervised by teacher and pupil volunteers, who are responsible for checking equipment out, keeping an inventory, and maintaining the equipment in operating condition.[6] Maintenance is imperative. In many schools, vigorous initial efforts have ended in disaster simply because no one on the staff took on the responsibility for cleaning and repairing.

Special equipment

Within the last few years, large pieces of special equipment have been purchased by many elementary schools under the cost-sharing provisions of the National Defense Education Act. The actual expenditure which towns must make for scientific equipment and supplies has been so substantially reduced that one portable laboratory table approved for purchase under the National Defense Education Act costs about

425 dollars, approximately half of its list price. The work surface of this table is four feet by two feet. The table is furnished with a twelve-inch stainless steel sink, a faucet and a four-gallon water tank. Built-in storage accommodates science kits for teaching magnetism, sound, light, heat, and measurement. Electrical outlets and a tank of propane gas for Bunsen burners are also built in. The exterior is resistant to fire and to chemical corrosion. The table itself, exclusive of the science kits, lists for approximately 325 dollars. Because this table can be quickly moved from room to room, and because its construction facilitates experimentation, its potential for science instruction is great. A number of companies manufacture these tables and their accessories; teachers should study the advantages and disadvantages of competing tables carefully because price is not always related to quality.

Many pieces of equipment are now specifically advertised for elementary school purchase. In the past, the planetarium has been far too expensive for elementary schools. Today, for less than one hundred dollars, schools may install a small planetarium in which ten children can view star projections of the northern and southern hemispheres, with constellation names and a projected ecliptic line. Because a dome is built into this planetarium, the image is not as distorted as it is with inexpensive ceiling projection. Naturally, the quality of the image leaves much to be desired, but it *is* an approximation of the night skies.

Models of the earth-sun-moon relationship range in price from a few dollars to two hundred dollars. The more expensive models are motor operated, and artificial "sunlight," falling perpendicularly on the "earth," simulates the seasons, the phases of the moon, and eclipses. These pieces of equipment are usually purchased for the entire school and are requisitioned by teachers as needed.

Science kits

Science kits are popular with elementary-science teachers and with school systems which have taken advantage of National Defense Education Act funds to upgrade their science equipment, even though ordering individual items from catalogs can save a great deal of money without diminishing in any way the quality of the materials purchased. The kind of expertise and time which can take advantage of these savings is not always available to busy classroom teachers and administrators. Kits *are* convenient. They are often attractively packaged and extravagantly advertised, and, at first glance, seem to include everything needed for high-level performance.

Many science kits cost more than the sum of the separate pieces because of expensive packaging, which is occasionally carried to ridiculous extremes. For example, individually wrapped paper cups and paper straws are sometimes included. Teachers and administrators should reject kits which include a large number of locally obtainable items like candles, straws, paper cups, drinking glasses, and dry cells.

The experiment manuals included in kits tend to obstruct and to narrow experimentation, because they are "cookbooks" which explicitly tell what to do and how to do it. Also, replacement of some of the items in a kit is frequently expensive, particularly when they are not standard pieces.

Materials and containers are often too flimsy to stand up under daily use, especially if they are plastic. Some science kits which begin classroom life neatly stacked soon become disorganized; neither teacher nor children succeed in storing all the items properly so that the case can be closed without damaging some of the contents.

Few kits contain enough materials for use by more than a handful of children at a time. Several companies produce class-size kits for experiments in the various sciences, but in order to keep prices low these kits are cheaply made and, as a result, breakage is high.

The price of a science kit depends on the method of packaging, the material of the case (wood or cardboard?) and of the equipment and supplies (plastic or metal?), the kind of manual supplied, and, of course, the number of standard, mass-produced pieces which are included. For prices ranging from fifty to one hundred and fifty dollars, many companies sell standard science kits which include a hundred or more separate items such as rubber stoppers, test tubes, hot plates, pulleys, spring balances, insect pins, magnets, iron filings, ring stands, etc. Specialized kits for nature study, embryology, plant growth, magnetism and electricity, water and its properties, heat, physiology, light, sound, air pressure, weather, and machines are also on the market. At least one kit is available for every area of elementary science.

Many teachers construct their own science kits, storing the materials in shoe boxes or in other containers of the right size, according to topics. These kits, augmented with special purchases, meet the teacher's and the class's science needs fully as well as the more expensive commercially prepared kits. Backed up by this basic equipment, the teacher draws on the supplementary resources of the central supply when necessary. The shoe-box kits should be clearly labeled, so that, when stacked, they can be quickly identified and removed. Each box should contain a list of all the items stored in it. A small, inexpensive multi-drawer plastic storage cabinet will hold the small, multiple-use supplies such as wire, screws, tacks, straws, and string. The inevitable inconvenience of maintenance and inventory will be eased by encouraging children to take on a measure of responsibility for maintenance.

Safety

Teachers should be ever vigilant in looking after the safety of their children. When we think about the potential hazards in scientific experimentation with relatively harmless materials, the fact that so few accidents occur in school rooms is a source of wonder. Children must be warned about all potential dangers. The teacher should *never* take it for granted that children are old enough to anticipate what can happen. Safety rules, which are cooperatively formulated, and direct instruction in handling scientific materials are necessary first steps in forming the attitude that accidents must be avoided.

Think of the hazards associated with household and school room electrical supplies. Most commercially manufactured electrical equipment operates on 110-volt alternating current. Under normal operating conditions, equipment approved by the Underwriter's Laboratory is safe. Sometimes, however, extension cords are stretched between an electrical outlet and the machine. If the cord is dry or cracked, exposing bare wire, it is dangerous and should be immediately replaced. Several cords connected simultaneously to one outlet are likely to be hazardous because of the possibility of circuit overloads. Teachers are often encouraged to substitute an electric hot plate for alcohol lamps, candles, or Sterno in the interests of safety. A defective hot plate is just as bad. Even if the hot plate is electrically safe, it should rest on a good heat insulator, such as a sheet of asbestos or an asbestos oven mat. The wiring on a hot plate is occasionally defective, and it should be checked by qualified persons before it is used. Commercially purchased equipment is sometimes hazardous. For example, a chick-hatching incubator devised for elementary school classes contains exposed 110-volt electrical connections. Children reaching into the incubator to handle eggs can easily brush against these contacts. Numerous suggestions for building heaters, incubators, and hot plates have appeared in the literature. Many embody shock hazards, and they should not be used unless someone who knows electricity certifies that they are safe.

Teachers are usually alert to the dangers associated with chemicals. For instance, ammonium dichromate which is used to simulate volcanic eruptions causes occasional skin rashes, and the eruption is accompanied by irritating fumes. The value of the ammonium dichromate volcano is insufficient to balance these risks, even though there is little chance of danger in a well ventilated classroom.

Children should be cautioned never to mix chemicals from their home chemistry sets at random, never to taste chemical mixtures, and to wash their hands thoroughly after using chemicals.[7] They should never use potassium chlorate (particularly if it is mixed with manganese dioxide from old dry cells) or chemicals like it. Many books of chemical experiments for children include potentially hazardous experiments. The recent rash of explosions which young adolescents have encountered in making rockets and bombs testifies to the need for sound safety practice.

Handling classroom animals can also be dangerous. White rats, guinea pigs, rabbits, and other animals can inflict painful bites. Of course, no teacher should permit children to keep such dangerous animals as black widow spiders and poisonous snakes. Even small snapping turtles are dangerous, and children should learn to avoid them. There are responsibilities as well as dangers in handling animals. Animals must be humanely treated, fed properly, given water regularly, and kept in clean cages. Cages should be locked so that they cannot be opened by children at will. In general, animal experimentation is to be avoided, because it inflicts needless pain and serves *no* scientific purpose. Films and other audio-visual aids are much better sources of information on the purposes and outcomes of animal experimentation. The higher wild animals should not be confined for more than a few days. A special permit from the state is often required in order to keep these animals in captivity.

When the potential dangers of scientific experimentation are thus described, they seem almost to forbid active science in the classroom. However, these dangers rarely occur, because children can be taught how to avoid them; with sufficient experience, they handle scientific materials easily, carefully, and confidently.

The teacher must be at least one step ahead of his class at all times. He should ask himself such questions as these: "What activities are likely to lead to cuts? To bruises? To fires? To electric shock? To bites? To inhumane treatment of animals? To noxious odors? To burns?"

Materials brought by children

The teacher can depend on one source of supply. In most communities, an appeal to children will inundate him with useful materials of all kinds.[8]

> After all the children had visited the center, plans were made to begin collecting supplementary materials which would enhance the science program but for which monies were not available. A suggested list of such materials went home with the children. The response was tremendous and the center was not quite ready for the deluge of materials that this request brought forth. The yield from this collection phase ran the gamut from live turtles to a stuffed great horned owl; from candles to old electric appliances; and such treasures as a bottle of volcanic ashes from Hawaii, to a worn, but prized, chipmunk skin.

The teacher can rely on the home for bottles of all kinds, for thread, for hard-boiled eggs, for special science toys and science sets. This source supplements, but does not replace, the standard classroom materials. In teaching the biological and earth sciences in particular, teachers will often ask children to bring in different kinds of rocks or to collect small animals or plants. Collecting live materials provides opportunities for practicing such sound conservation habits as picking only common plants.

The teacher never knows exactly what *will* come in, because children sometimes forget, and parents may object to furnishing materials which the school should supply. Nevertheless, the resources of every community for obtaining simple science materials are vast, and the teacher should not abandon a promising investigation because the necessary equipment is not immediately at hand.

Tools and hardware

Each classroom should own its own basic tools. The most useful for children are hammers, saws (crosscut, hack, and jig), a bit brace and bits, a hand drill, an assortment of screws and nails, and glues for wood, metal, and paper. Each child will probably not use all these tools, and some may use none, but those children who do use them should receive proper instruction.

Equipment for the new elementary-science programs

If you are teaching one of the new science curricula, you will find that the Teacher's Guide gives helpful suggestions for selecting the most useful kinds of equipment. In addition, kits of equipment are commercially available for school systems which have adopted these programs. These kits may include only those materials which are difficult to gather, or, in some cases, contain virtually all the equipment on the equipment list. Specially designed pieces must usually be ordered from a designated supplier.

The rationale which guides these projects in making supplies and apparatus available is clearly defined by the Elementary Science Study:[9]

> If science in the elementary school is to be based on the experience a child can gain with his own hands and eyes, then laboratory equipment is of prime importance. Characteristically, equipment should be designed so that it is safe, easy for each child to handle at his own desk, adaptable, sturdy, reasonably accurate, easy to store and maintain, and inexpensive enough for elementary schools to buy in quantity. Ideally, teachers and students should not be supplied only with the neat kit, the package that works, the thoroughly tested output of the developers. As scores of elementary teachers know, a great deal of equipment can be improvised

> out of rubber bands, toothpicks, tin cans, soda straws, and other readily available materials. Indeed, this creative process is frequently encouraged in our units, and much of our equipment is of this casual nature. But this is not enough. Obviously, carefully designed equipment is needed also, and no teacher should be expected to elaborate such devices from scratch, to ensure their technical accuracy, nor take the time to produce them for each child. For both technical and economic reasons, therefore, some apparatus should be developed by specialists and made available in classroom quantities.

Let us examine the kinds of equipment required for some of these curricula. Consider, for example, the lesson on "Observing the Weather" in *Science—A Process Approach.*[10] This lesson, written for the second grade, is the second exercise in which the thermometer is used to help interpret the weather and make weather observations. The teacher's guide suggests that the following items be provided: a minimum of three "*easy-to-read*" thermometers with Fahrenheit scales; three large cans of water, each at a different temperature, and each insulated with layers of newspaper; a temperature chart; a weather chart; fifteen feet each of red and white ribbon (for making the temperature chart); and an optional demonstration thermometer.[11]

The following materials are listed for the exercise on "Similarities and Differences": a set of shapes for each child; many different common objects such as balls, cylinders, sugar cubes, blocks, buttons, a variety of kitchen utensils; smooth, broken, flat, and sharp-edged rocks and pebbles; a collection of red objects and of green or yellow ones.[12] In "Observation of Color and Color Changes in Plants," a number of chemical materials are necessary: red cabbage or blackberries, red begonia or coleus leaves, beets, ammonia or baking soda, vinegar, litmus paper, 1000-ml. beakers (or one-quart Pyrex pots), an old handkerchief, four 250-ml. beakers or Pyrex custard cups, sodium thiosulfate (photographer's hypo), a hot plate, tincture of iodine, medicine droppers, teaspoons, small jars or paint cans, and tongs.[13]

Whenever the activity is experimental—that is, when conditions must be changed and manipulations made—the list of requirements tends to be longer. The amount of time which the teacher can save if she has the accessory kits on hand is therefore substantial. Many items, however, are already on hand, either in the school or at home.

Even in the experiences for older children, the American Association for the Advancement of Science course is not overdependent on specialized equipment or supplies. For example, the list of suggested materials for "Image Formation—The Pinhole Camera" is well within the reach of any elementary classroom: a photographic enlargement, a camera (optional), cardboard boxes for each child, white paper, opaque cardboard, a desk lamp, unlined index cards, metersticks (one for each two children), decimeter rules (one for each pair), one or more slide projectors, several cardboard screens, and a 35-millimeter cardboard slide with a cut-out.[14]

For "The Effect of Temperature on Rate of Change," two bottles of corn syrup, some granulated sugar, two teaspoons, a hot plate, a pot in which to heat water, ice cubes, a clock with a second hand, and hot and cold water are required.[15] Each group of children needs in addition two glasses, four Alka-Seltzer tablets, a Celsius thermometer that measures from zero to one hundred degrees, a glass plate or mirror, and four to six marbles.[16]

The Elementary Science Study was the first of the major elementary-science projects to prepare kits for classroom use. These kits are still considered by the Elementary Science Study to be in their early developmental stages:[17]

> [The units] do not constitute a curriculum, but they may provide the first of the threads from which curricula may one day be woven.
>
> Further development will rely heavily on the reactions of the teachers who will try the units in their current form. They will all use the materials in their own ways, in their own classrooms, with their own pupils. In each of these situations the learning will develop differently. We are hoping that teachers and other readers will let us know their reactions, and we will warmly welcome any comments and evaluations they may want to make.

"Small Things," a unit for middle and upper grades, is a series of investigations of onion cells, differential stains, human epithelial cells, plant cells, pond-water organisms, the structure of non-living things, and yeast-cell growth. These activities are extraordinarily well presented. They are provocative without being so heavily structured that pupil and teacher initiative and freedom are suppressed.

The Elementary Science Study "Small Things" kit contains these materials, which are sufficient for five children to work individually: five simple but practical microscopes with a basic magnification of sixty; five hand lenses; five tweezers; five eyedroppers; five balances constructed out of soda straws, wood bases, screws, and pins. The teacher's kit provides additional supplies for thirty children: one gross of microscope slides; two hundred plastic cover slips; lens paper; methyl-cellulose solution; methylene blue stain; Lugol's iodine stain; eosin Y stain; toothpicks; one pound of calcium chloride.[18]

Supplies such as scissors, masking tape, facial tissue, cotton, bottles, onions, rubbing alcohol, potatoes, and lettuce must be obtained locally. Some items *must* be ordered from biological supply houses, e.g., amoeba and euglena cultures.

Supplementary materials, such as the film "Paramecium, Euglena, and Amoeba," have been specially produced for this unit. This fifteen-minute motion picture "emphasizes the various questions about protozoa with which the children have been concerned." Several 8-millimeter film loops, each taking no more than a few minutes, show some of the common protozoans which inhabit pond water.

Naturally, the Elementary Science Study kit for "Gases and Airs" is quite different. Student kits, for two students only, include newly designed racks and trays, plastic tubes, a syringe pump, and a variety of other items. The teacher's kit duplicates these pieces, and adds a larger syringe pump, rubber sheeting, mung beans, pyrogallol, and sodium hydroxide. Some supplies, such as vinegar and birthday candles, must be obtained locally.

The "Gases and Airs" unit is twenty-five lessons long, a total which may be increased by selecting from the supplementary experiments in the appendix, or shortened to as few as sixteen lessons. In addition, a number of film loops may be purchased for the purpose of adding demonstrations not provided for in the kit, or for giving children an opportunity to look more closely at experiments which they have already done. These film loops are excellent devices by which to orient teachers to experimental techniques.

On the assumption that there are thirty children in the class, fifteen two-student kits will cost about eighty dollars, to which must be added the fifty-dollar cost of the teacher's kit. With the film loops, worksheets, and spare parts, the total for each room is approximately two hundred dollars. The Elementary Science Study estimates that about 45 percent of the teacher's kit and about 70 percent of the student's kit is reusable.

For thirty students, five-student kits for "Small Things" will cost approximately ninety dollars, with an additional twelve dollars for the teacher's kit. If the film "Paramecium, Euglena, and Amoeba" is rented and only a few of the eight available film loops are purchased, the cost per room will be about 150 dollars. The teacher's kit cannot be reused, although 70 percent of the student's kit may be used again.

The more unconventional the experiments, the less compatible their equipment requirements are likely to be with the usual kinds of elementary-science equipment. At first glance, the cost of adopting the Elementary Science Study units appears to be much higher than that of traditional elementary-science instruction. Cost comparison is misleading, however, not only because sets of textbooks need not be purchased, but because elementary schools do not often buy apparatus and supplies for individual experimentation, and, as a result, there is no valid basis for comparing costs.

The activities in *A Sourcebook for Elementary Science*,[19] *Science Experiences With Ten-Cent Store Equipment*,[20] and in the elementary-science textbooks are almost always restricted to conventional pieces of apparatus and to improvised and child-supplied equipment. For instance, the third-grade edition of a well-known textbook series suggests that these materials be on hand for the unit on air: balloons, paper fans, a bicycle pump, an aquarium, glasses, jars, a yardstick, an aneroid barometer, a handkerchief, soil, a sponge, dishes, and a thermometer. The chapter on energy in a fifth-grade text lists these items: string, a weight, a vacuum bottle, jars, a thermometer, empty milk cartons, a wooden board, a spring balance, a ruler, sand, coffee can lids, marbles, white cloth, plastic bags, nails, pulleys, and a yardstick.

Once the basic supplies and equipment have been obtained, a large number of science experiences can be presented with little need for supplementary materials beyond those which the children can supply. When new problems or different ways of investigating old problems are tackled, however, conventional materials are not completely satisfactory. It is for this reason that the Elementary Science Study, like the other projects sponsored by the National Science Foundation, has licensed the commercial manufacture of its unique apparatus.

The task of deciding what equipment and supplies are necessary for the year's work is simplified by adopting a pre-planned curriculum—either a conventional textbook or one of the new programs. If the curriculum is less structured, the teacher must try to anticipate equipment needs and be willing to take certain risks. Partly for this reason, structured programs appeal to inexperienced teachers and to those who, for one reason or another, are unwilling to chance a day-to-day pursuit of the goals of science education.

There are many sources of information for purchasing, ordering, storing, and using scientific equipment and apparatus wisely. The following are particularly recommended:

1. *Purchase Guide for Programs in Science and Mathematics*, Council of Chief State School Officers, Boston: Ginn and Co., 1965. This book is available in every superintendent's and science supervisor's office, and in the offices of many principals. It provides detailed lists of equipment according to field, e.g., biology, chemistry, elementary science (basic, standard, and advanced). The book describes each item and its uses in detail, and includes a section on elementary school facilities (pp. 335–338), and on laboratory safety. Lists of audiovisual aids sources and an annotated bibliography of science books (many on the elementary level) in the various fields are also included.
2. Hone, E., et al., *A Sourcebook for Elementary Science*, Harcourt, Brace and World, N.Y., 1962. This is a good source of many simple science activities. It contains an excellent chapter (Chapter 1) on adapting

the elementary classroom to science. Chapter 28, "Working with Science Materials," gives many suggestions for handling materials safely and for storing chemicals and other substances.

3. Piltz, Albert, *Science Equipment and Materials for Elementary Schools* (Washington, D.C.: U.S. Department of Health, Education, and Welfare, Office of Education, OE-29029, 1961), Bulletin 28, 30c from the U.S. Superintendent of Documents. This is a source of wise and time-tested suggestions for planning the use of equipment, storing it, and evaluating it.
4. *Safety thru Elementary Science*, Washington, D.C.: National Commission on Safety Education and the National Science Teachers Association, 1949. This pamphlet is out of print, but is available in many college and university libraries. It is the most complete discussion of safety education through science and in science activities published to date.
5. "*Science Equipment in the Elementary School*," *Cornell Science Leaflet*, 56: No. 2, December 1962. Excellent suggestions for handling practical science materials, for purchasing inexpensive substitutes, and for preparing a place to work.

Summary

Lack of equipment, facilities, and supplies is one of the traditional impediments to progressive science teaching in the elementary schools. Busy teachers have little time for improvising equipment or for supervising the construction of make-shifts. Therefore, although there is an important place for the many useful materials from the home and the ten-cent store, there is a real need in the school for many standard pieces of science equipment which are both durable and effective for special uses. The classroom should have adequate working space, augmented by sinks, electrical outlets, and storage space. Even with good supplies and work facilities, teaching will be improved by a special science room or by a science center from which teachers may requisition the less frequently used or more expensive pieces of apparatus.

Teachers will receive much help from local science supervisors in planning for science instruction and in ordering and requisitioning science equipment. Unfortunately, most school systems lack science supervisors; teachers in these towns should turn to science teachers in the junior or senior high schools, who are waiting to help. Most elementary-science textbook series provide detailed lists of required and supplementary pieces. The new elementary-science programs have also begun to make available special kits which include the basic items for their activities. These kits are somewhat expensive and quite different from the traditional kits and items of equipment usually suggested.

Expense, however, is not really a meaningful standard of comparison, because in the new programs the cost is for individual pupil experimentation, whereas in traditional instruction it is for demonstrating to the whole class. The important issue is philosophical and psychological. To what extent are schools willing to accept the goals of science education by giving each child direct experience with the materials of science?

Whenever children observe, handle, manipulate, and build, they will encounter hazards to their personal safety. Safety rules which are cooperatively formulated and strictly enforced will help to avoid serious accidents. There are dangers whenever 110-volt electricity is used, chemicals are handled, or animals are kept in the room. These dangers, although never more than a moment away, are easily avoided by children who are properly instructed and who approach experimentation cautiously and attentively. One of the most important behavioral objectives of elementary-science instruction is the incorporation of sound safety practices into the child's daily living.

For further study

1. To what extent is it legitimate to teach textbook-centered science, or to omit science altogether because of inadequate supplies and equipment?

2. As a cooperative class project, make an analytical study of the elementary-science facilities and equipment of one of the laboratory schools in which you do your practice teaching. Is the school equipped for modern science education?

3. Ask an elementary-science supervisor what he thinks the most important problems of elementary-science teaching are. How does he rate facilities and equipment in comparison to curriculum organization, teacher preparation and interest, and community attitudes?

4. Compile a list of equipment which is required for teaching one series of lessons in a new science curriculum. Estimate its cost if everything were to be purchased from a scientific supply house. Which items can be easily and inexpensively improvised?

5. Apply the criteria for selecting scientific apparatus and equipment to the purchase of these items for (a) a second grade; (b) a fifth grade. Select whatever mode of science teaching that you find most interesting.
   (a) Aneroid barometer.
   (b) Anatomical model of the human torso.
   (c) Electrolysis apparatus.
   (d) Radiometer.
   (e) Aquarium, twenty-gallon tank.
   (f) Commercial mineral and rock collection.

6. Write a critique of a commercially prepared science Inquiry kit.

7. Study the safety hazards which children may encounter in the experimental portions of any one of the new elementary-science curricula.

8. "Manufacture" a shoe-box science kit for one unit which contains enough material for several children to experiment individually. How expensive is it? How durable is it likely to be?

9. Compare the cost of materials for an entire year of a conventional textbook program in science with that of one of the new programs. What reasons can you propose for the difference?

10. How valid is this statement: "Every effort should be made to make use of simple equipment in order that the attention does not become focused on the equipment rather than on scientific facts, ideas, and principles"? Under what circumstances is the statement oversimplified?

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done under a grant from the National Science Foundation, published 1965 by Houghton Mifflin Company, Boston, Massachusetts, p. IV.

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To speak of "evaluation" is to open a Pandora's box of conflicting meanings, interpretations, and impressions, because the precise meaning and function of evaluation are obscure. All educators believe that evaluation is good, and therefore every elementary school methods textbook conscientiously grapples with it. Of course, evaluation is more than giving tests, marking papers, or locating each child at some exact percentile on a standardized examination. Evaluation is not the same thing as probing the child's knowledge of the solar system, his flexibility in new contexts, or the depth of his understanding of the role of the scientist in American society. The meaning of evaluation has been well expressed by Pauline Sears:[1]

> A teacher's evaluative activities go far beyond marking papers; they include attention to many experiences of success and failure, of expanded or restricted autonomy, of immediate and long-term goal-setting, of recognition of individual progress, and of attitudinal responses to divergent behavior. These evaluative behaviors have the characteristics of positive and negative reinforcers, and, as such, are motivationally relevant to learning.

What is required, instead of the unrelated behavioral cross-sections which emerge from measurement, is assessment of child growth in those aspects of science which the teacher holds to be important. The intent of evaluation is to learn what each child is like, not to find out how he differs from his fellows. This conception of

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Evaluation in elementary school science

evaluation is not new, but it is rarely achieved in elementary-science instruction.

Wise decisions require evaluation

Evaluation in elementary-science teaching is necessary for many reasons. Teaching, as an art form, is a process of making decisions. The teacher must decide whether the class is ready for an experimental sequence on electricity, whether sufficient resources are on hand, and whether electricity is a better subject for study at this time than insect life. He must decide whether the class is prepared to participate freely in planning, and whether his children are skilled enough in cooperative work to make small-group investigation worthwhile. Even the aura of permissiveness or authoritarianism in his classroom is the result of a decision which may or may not have been explicitly formulated.

Wise decisions should take such factors as these into consideration: What are the children like? What do they know? How well do they read? How do they work together? What are they interested in? Which children are creative? Which are rote learners? For example, what prior knowledge of electricity and electromagnetic phenomena do these children possess? If they are unaware that a current flowing through a wire generates a magnetic field around the wire, and if they have no firsthand experience with magnets, their study of electromagnetism must begin with simple magnets. It may be practical to utilize more knowledgeable children as group leaders in planning small-group investigations.

The wisdom of the teacher's decisions is a function of his knowledge about each child. If he knows that the children have previously been successful in analyzing simple problems, he and the class can begin with a greater probability of success. Surely, no teacher will jump into free, unstructured Inquiry instruction unless he is confident that his class is well prepared. He must also be aware of the inner forces which affect his class, so that he can strive to form or to re-form attitudes and appreciations which he believes are important. It is not difficult to assess subject-matter knowledge and to judge whether or not children are adequately informed. It *is* difficult to determine the children's growth in the process and appreciational-attitudinal aspects of the sciences.

One of the important, yet often rejected, functions of evaluation is that of providing sufficient feedback to each child so that he may assess his own progress. Children are often unaware of their own deficiencies. They may admit to "not being good in science," or to disliking science, but this vague, imprecise judgment is neither a stimulus to remedial action nor an instructional guide. According to modern learning theory, immediate feedback enables the learner to change his responses more quickly and more effectively. In order to provide pertinent feedback, evaluation must continually give the child information about his own development. The customary end-of-the-marking-period testing to assess total learning is harmful, because its interpretation comes too late to help the child in his day-by-day learning. It is true that some children are satisfied with minimal achievement; feedback they receive is unlikely to motivate them. For others, continual evaluation is of little value because they quickly modify their responses to conform to what they know the teacher wants. They adjust, not because of the intrinsic value of doing things differently, but because they seek the reward of academic virtue. It is an educational truism that the real goals of the teacher are revealed by his written and oral testing. No matter how much time he devotes to the non-informational aims of science instruction, his children will soon know how to prepare for tests which stress recall of facts. In this sense, the kind of evaluation is a commentary on what the teacher thinks are the real goals of science instruction.

In short, if wise decisions about classroom teaching are to be made, if there is to be a match of content and process for individual children, the teacher must not settle for a few scattered bits of information. The complexity of science learning, and the number of more or less discrete skills, abilities, concepts, and principles which are encompassed in the learning process, disqualifies decision making that ignores longitudinal sampling of these aspects of learning.

The administrative function of evaluation

In addition to decision making, there is an administrative function in evaluation. Parents wish to know what kind of progress their children are making in science, and report cards rarely provide more than a letter grade or a percentage mark. Parents may be satisfied if these marks are high, despite the fact that they are given little positive information. How often are parents informed on the child's success in interpreting scientific phenomena, his scientific likes and dislikes, the kinds of books he reads about scientific phenomena or scientists, and the extent to which he is superstitious?

Schools must either promote or retain children in each grade. Promotion which is not automatic must be based on evaluative evidence. In addition, evaluative records are often essential for remedial instruction or for special classes of gifted children.

The function of evaluation is to see each child whole, as a total organism, not merely a bundle of a few isolated strengths or weaknesses.

As Cronbach remarks, "An ideal evaluation would include measures of all the types of proficiency that might reasonably be desired in the area in question."[2] Every child is many-faceted, a complex of countless submerged strengths and weaknesses, fleetingly visible here and there. The usual objective test is scored as a totality, or, at best, is sliced into a few deceptive sub-scores. The student who scores high on a reasoning test may not have been forced to reason at all if he has previously encountered similar problems. He may have been tested only on simple recall, not reasoning. If each item on the test is written for some specific purpose, such as measuring ability to select relevant from irrelevant data or recognition of hidden assumptions, assessment of these individual elements of behavior and of learning becomes feasible.

The success of instruments and techniques for evaluation depends on a complicated interplay of child-teacher-school relationships. For example, children who show severe anxiety are less likely to achieve well under such pressures as timed tests; children of moderate or low anxiety are much more likely to do well. Certainly, no one expects to find in the authoritarian classroom much evidence of progress toward autonomy in science learning and toward strengthening the higher aspects of cognitive and affective behavior.

In addition, students must know what the teacher expects of them: they should have some reasonable idea of where they are going and of what they are trying to do. One of the values of teacher-pupil planning lies in the acceptance of cooperatively planned goals which are genuinely cooperative, so that children know what they are to do and have some idea of how to do it. This kind of planning may help to reduce the undesirable anxiety of some children, particularly in taking the paper-and-pencil tests which children traditionally regard as the real basis for report cards.

Who evaluates

Although the standardized test does have its place, it is distinctly inferior to informal classroom evaluation. The teacher is responsible for selecting and remaking the curriculum for his children. He is also the evaluator, because he is the *only* person who knows each child and his total group. A test standardized on national norms is a weak evaluative reed on which to lean. If his curriculum grows out of teacher-pupil interaction, outside tests which ignore this interaction are unlikely to be valid, whatever their statistical reliability. The burden of responsibility inevitably rests on the teacher and on his children. There are no nationally available tests whose validity for measuring growth in Inquiry skills has been proven. The teacher *alone* knows what he is trying to do and what success he and his class have attained. He *alone* is in a position to know whether or not a particular child is an intuitive thinker, whether he is a leaper, and whether he is rigid in his behavior or is unable to cooperate with other children.

Informal evaluation

The labyrinthine evaluative processes described above are apt to strike terror into the heart of the prospective teacher. How is it possible to look at each child "whole," to keep track of him as an individual, and, at the same time, to carry on the daily business of the classroom, which is a busy round of the academic, social, and physical? This kind of evaluation is not often practiced in the elementary school classroom, despite the many years for which continuous evaluation has been preached. Surely this is not because teachers are short-sighted or are content to give lip-service. Most teachers accept the need for progressive evaluation. Why, then, is the evaluative outlook so bleak? Why is it difficult for the classroom teacher to know in detail and with deep insight that Johnny, who cannot plan an experiment, is blocked because he cannot separate the pertinent variables, and that Jane never associates verification with proposing hypotheses? There are several reasons for this.

First, evaluative instruments are crude. In a sense, they are like a librarian who classifies all science books into physical, biological, and earth science categories, without noting that one book is a chemistry of amino acids, a second is on the structure of viruses, and a third describes the mineral components of granites. Admittedly, evaluative tools are neither powerful nor sensitive, and few have improved much in the past two decades.

A second reason is that only within the last two decades has important progress been made in the theory of evaluation, and this new evaluative sophistication has not yet been incorporated into the action structure of practicing teachers. This is the case in elementary science evaluation, which has lagged behind secondary and collegiate assessment. The "whole-child" concept has been narrowed to academic achievement, which is measured by tests of recall, and to interest, intelligence, and social adjustment. The fine structure of the cognitive and affective processes has just begun to come into view, much as the fine structure of the atomic nucleus has just begun to make sense to nuclear physicists. When one contrasts the hundreds of millions of dollars which have been spent in the search for nuclear knowledge with the almost total lack of support for evaluation of child learning, the fact that there has been any progress is heartening. But is is not surprising that teachers who have traditionally not considered science to be as important in the curriculum as arithmetic or reading are not in a position to apply what is now known in science evaluation.

A third reason is that a formal, thorough program of evaluation is inordinately time-consuming. The teacher who attempts to record the multiple varieties of learning achievement for each child, assuming that the proper evaluative tools are at hand, is a clerk, not a teacher. So minor a task as correcting a short written quiz once or twice a week is exhausting if the strengths and weaknesses of each child are recorded and reported to him. Too often, records which must be maintained at the expense of other worthwhile activities gather dust. Keeping records is time-consuming; interpretation takes even more time. In actual practice, "troublesome" students, those children who for emotional, intellectual, or social reasons disturb the others, preempt the time that might otherwise be used for detailed record keeping. Parents are familiar with the soothing phrases, the easily recognized and all too often meaningless testimony, of an uninformative report card. These words, which are not deliberately made obscure, emerge from the many stresses to which the teacher is exposed in a formal, time-harassed evaluation.

Evaluation is obviously necessary, and many different kinds of evaluative knowledge about each child are desirable. How are they to be obtained in the classroom? In a subject such as elementary science, which is often not a formal, rigidly scheduled subject, the teacher must rely on the accumulated evidence of her senses, resorting to written records of each child's progress only if exciting and vital classroom science is unimperiled. Evidence of pupil growth will come from hard listening and hard looking at everything that children do and do not do in class. This informal observation is almost devoid of record keeping. The professional teacher is able to sense the general strengths and weaknesses of her class. As she gains experience in Inquiry, she will focus on those evidences of Inquiry learning which are important. This information is impressionistic, the subject of quickly expressed and stored decisions as to whether or not Johnny has proposed a wildly irrelevant scientific hypothesis, or whether he has learned to exclude meaningless aspects of motion pictures.

These remarks are not intended to deny the importance of written tests and records. Written tests provide information which cannot be gathered by skilled observation. Data to corroborate or to deny the validity of teacher observation of child learning may also be obtained. These functions of written tests, and their appropriate techniques, are described in this chapter in some detail.

Statistical interpretation is relatively unimportant in elementary science teaching. Of course, the teacher should be able to distinguish between good and bad hypothesizing, and between relevant and irrelevant application of principles. To the degree that the validity of his assessment of behavior is important, the experienced teacher is sufficiently knowledgeable to make quick decisions and to refine them so that they are both reliable and meaningful. The information that a child consistently fails to connect three dry cells in series is significant to the teacher; the information that 65.3 percent of all children of that age can succeed in this task is not. The pertinent question is this: Can each child carry out the necessary steps in order to complete the activity successfully? If not, why not? How should his strategy and tactics be revised to increase the chances for success?

In informal evaluation, grades are not awarded, nor are comparisons between children sought. There is time later on, in the formal science of the junior and senior high schools, for this kind of measurement and for the narrowing of assessment to paper-and-pencil testing.

The domains of science evaluation

For the purposes of this book, evaluation of classroom learning and behavior is more or less arbitrarily divided into three domains:[3]

1. The *cognitive* domain of knowledge and intellectual skills.
2. The *affective* domain of emotional and attitudinal behavior.
3. The *psychomotor* domain of physical and manipulative skills.

The cognitive domain, or some part of it, is the usual focus of science evaluation, because it is concerned with knowledge of subject matter and with the intellectual skills which contribute to mastery of subject matter. These aspects of learning have traditionally been accented in science instruction. Despite many years of serious study of the cognitive domain, which is spread over the broad spectrum from simple recall of isolated facts to synthesis of new ideas, evaluators have not yet agreed on how to assess competence in the higher cognitive processes. The publication in 1956 of the first volume of *The Taxonomy of Educational Objectives* marks a turning point in this struggle to delineate and to make meaningful what has been fragmentary and submerged—although we must add that many educators do not agree that this is the case. We believe, however, that it is now possible to arrange intellectual skills into a hierarchy with some confidence of consensus as to placement and identification. Once these skills or abilities are known, teachers should be able to recognize behavior which represents these skills. With this criterion for "behavior" in mind, the actual behavior of children, as observed or inferred by the teacher, becomes the raw material of evaluation.

Cronbach has described two types of behavior which provide evidence of higher cognitive learning. (See Chapter 2, p. 92, for a more extensive treatment.) One type, "applicational transfer," is a more or less immediate application of new skills and knowledge to related problems.[4] For instance, a child who understands that water-carried rock and soil is usually "sorted" as water velocity decreases should be in a better position to explain why conglomerate rocks are composed of unsorted particles. The fact that a child is unable to make this or any other specific application does not prove that he has failed to understand the generalization. After all, much that is now self-evident in the light of scientific advance was not so plain to great scientists in the past. For example, when Jacobus van't Hoff conceived of the tetrahedral carbon atom, Adolph Kolbe, a famous German chemist, derided van't Hoff's vision as "fanciful nonsense" and "supernatural explanation," and refused to apply this new conception of the atom to problems in carbon chemistry. Only when a child consistently fails to apply principles and processes in situations which do not appear to be conceptually difficult should the teacher minutely study the child's pattern of thinking.

The second kind of transfer behavior is "*gains in aptitude*," which requires a much longer time period for germination.[5] This behavior is the child's working frame of reference for looking at problems which he encounters. In another sense, it is mastery, at some level of competence, of the process-components of science. The student grows in sureness and in the mental agility required to tackle more or less complex problems and ideas, to define problems so they are feasible, to sense whether or not his hypotheses are testable, and to approach and carry through an investigation in as accurate, controllable, and unbiased a fashion as possible.

The levels of the cognitive domain[6]

1.00. Knowledge The child who remembers appropriate facts, concepts, principles, structures, and phenomena has learned. Knowledge, of course, is dependent on memory, even though each item recalled may be somewhat restructured. "Higher" categories of the cognitive domain include judgments, relationships, and reorganization of remembered knowledge. This "knowledge" behavior is conveniently divided into several sub-behaviors in a logical, although not necessarily psychological, order of complexity.

1.10. Knowledge of specifics Knowledge of specifics, which is recall of individual and unrelated items of information, is the simplest category of cognition. The skills described below are believed to belong to this category:

1.11. Knowledge of terminology Knowledge of terminology is familiarity with verbal and non-verbal symbols and the ability to associate symbols with their referents. All students of science must become familiar with the vocabulary of science in order to learn most efficiently. Many scientific words are useful because of their power, and their frequent occurrence in scientific writing. For example, "magnetic field," "test tube," and "animal" are as unavoidable as they are necessary. The child who knows the meaning of the word "animal," who includes insects in this category and excludes trees, has mastered an important scientific principle. Of course, *familiarity* with scientific terms does not mean that children will use them with the precision of mature scientists.

1.12. Knowledge of specific facts and sources of information The sun's distance from the earth, the number of planets, and the number of legs on a mature insect are typical of the kinds of knowledge which have been taught in the past. This category also includes knowledge of ideas and principles when learned as facts. Children should know as many facts as possible, but never at the expense of meaning and relationships.

Children are not often tested on their knowledge of where to look for facts, concepts, explanations, and principles. They should know that such authors as Herbert Zim and Harry Sootin are reliable and authoritative, and that their books are well worth looking into for specific information.

1.20. Knowledge of ways and means of dealing with specifics This aspect of knowledge covers the ways in which facts, ideas, and information are organized, brought to hand, and assessed. It encompasses the formal structure of science. Children at this behavioral level recognize that science is an organized body of facts and ideas and that scientists usually test hypotheses against experimental and observational evidence—although they are not necessarily able to use these procedures themselves. This category of knowledge, which is somewhat more abstract than category 1.10, is divided into five sub-categories:

1.21. Knowledge of conventions Knowledge of conventions is knowledge of the accepted ways of manipulating ideas, facts, and events. Every scientific discipline characteristically includes some traditional but arbitrary usages. For example, astronomers speak of the sun as moving through the sky, even though this phrase is not accurate; chemists who write about the hydrogen ion symbolize it as H^+, even though each hydrogen ion in water is associated with an indeterminate number of water molecules; and in the elementary school force is often described in terms of effort and push or pull, despite the limitations of these words. Knowing how to work together in the classroom, the form to follow in writing reports, and the units of measurement are also included in knowledge of conventions.

1.22. Knowledge of trends and sequences This sub-category includes the time relationships of events, both physical and conceptual. It is obviously on a higher intellectual plane than the previous kinds of knowledge. Achievement demands knowledge of events and of their succession, and thus some element of causal thinking is perhaps implied, even though formal causal thinking, as such, is on a higher level of abstraction.

The child who is aware of the succession of the seasons, of the sequence of mountain building and mountain erosion, and of the water cycle evinces a knowledge of trends and sequences, although he is not necessarily able to predict future events from these trends. Well-founded prediction requires that the child add the cautionary injunction that the future is predictable *if* the trend continues and other factors remain constant. The child who can make this kind of prediction is operating on a level far above simple "knowledge of trends and sequences."

1.23. Knowledge of classifications and categories The scientific disciplines are grouped into sub-disciplines and specialties of various kinds. Classification is a powerful scientific tool, because it summarizes the ways in which members of a class resemble each other and differ from members of other classes. Classification simplifies the task of the learner and the experimenter. For example, the division of flowering plants into families with related structural and evolutional characteristics enables the botanist to recognize an aster because of its flower structure. Many botanists quickly identify plants which they have never seen before because of their general family characteristics. What is perhaps more important, they know almost immediately what the plants are not! To take another example, the name "metal" immediately reminds the chemist of the chemical and physical properties of metals, and it suggests methods of handling and analyzing. Of course, no one can know more than a fraction of all the scientific classificatory schemes which have been invented, nor can he master all the schemes for any one science.

Although it is desirable for children to apply this kind of knowledge to new problems, achievement in this category requires only recognition of relevant classes and recall of the criteria for selecting members of the class.

1.24–1.25. Knowledge of criteria and methodology This sub-category includes awareness of the standards by which actions, facts, processes, evaluations, and opinions are judged. It includes judgments of the factors which make for experimental adequacy: elimination of irrelevant factors, good sampling, and sufficient repetition, accurate and logical recording of data, and limitation of generalizations. It also includes judging published sources by their cogency, precision, lack of bias, and by the reputation of the publisher and author.

Statements of criteria wrenched out of their immediate context are likely to be meaningless; they have meaning only if used for evaluation, which requires a much higher level of cognitive skills. In fact, all of the previous sub-categories of cognition are meaningless in and of themselves. They are significant only in the proper contexts.

1.30. Knowledge of the universals and abstractions in a field This category includes the kind of knowledge whose acquisition has traditionally been an important goal of science instruction. It is more than awareness of either the structure of science, or the way in which that structure is organized. As used in this book, "knowledge of the universals and abstractions in a field" implies some degree of insight into the meaning of the great ideas of the sciences.

1.31. Knowledge of principles and generalizations This sub-category is exemplified by recall of the salient laws and principles of the sciences—for example, the law of gravitation, and "protoplasm is the physical basis of life." Such recall, however, is not the same as the application of ideas in order to explain events and phenomena. Principles and generalizations are derived from many different events and from the cumulative experience of centuries. They are generalized descriptions, not explanations; they are the essence of happenings, their common elements. Because they are abstract, they have a general power. This sub-category, however, directs attention to remembering principles and generalizations as a preliminary to their application.

1.32. Knowledge of theories and structures This class includes recall of the theories which unify the principles and generalizations of the sciences. The learner who is familiar with the theory of evolution or with kinetic-molecular theory can state the theory's important ideas and its subsidiary assumptions and principles. Each discipline is characterized by certain theories, some of which are more soundly based than others. The theoretical structure of the physical sciences is better interrelated and more easily derived from fundamental laws, assumptions, and observation than the structures of the biological and the earth sciences (with the exception of astronomy).

2.00. Comprehension Comprehension includes the intellectual skills and abilities, such as the strategies and general techniques for studying and learning. Comprehension, although "higher" than recall, is still relatively less complex than application or evaluation.

To comprehend is to be aware of the significance of knowledge—to show insight into its meaning and intent, rather than just to repeat words. Everyone has had an experience in which the meaning of a difficult statement is almost instantly cleared up by a textual clue.

"Comprehension" may be conveniently divided into these three components: translation, interpretation, and extrapolation.

2.10. Translation Rewording a statement is a sign of comprehension. In order to transform a statement into an equivalent statement in his own words, a learner must be acquainted with the specifics, the ways and means of dealing with these specifics, and the relevant universals and abstractions. Consider, for example, translation in its usual sense. Even in scientific translation, the intent behind the words, not their literal meaning, must come through. For example, a non-chemist may, with the help of a dictionary, be able to translate a paper on chemistry from Russian into English, but he will miss the delicate shadings and the technical nuances, because he does not *think* like a chemist.

Mathematics is an indispensable language for scientists. It is useful not only because it simplifies the scientist's task of extracting all the information out of his data, but because it enhances prediction as well. Because it is a language, mathematics must be translated by most students of science into their own language. Graphical analysis of data is another mode of translating relationships. The transformation of columns of data into a graph whose characteristic curve suggests previously hidden relationships is such a translation.

2.20. Interpretation Interpretation is perhaps the highest form of comprehension, because the interpreter must not only select the ideas which give life to an event, a phenomenon, or a statement, but he must also grasp their meaning and the relationships and limitations which define them. Interpretation is difficult because the interpreter must suppress his own biases, lest interpretation become misinterpretation. The individual elements must be reorganized and significant portions selected according to some criteria. Certain conditions or possibilities are inferred as logical deductions even though they are not explicitly stated in the data.

For instance, the fact that man can live for weeks in a satellite hundreds of miles above the earth's surface may be interpreted to mean that the chances of colliding with a meteor or of radiation hazard at that altitude are slight. The generation of heat and light as a candle burns is interpreted to mean that the products of combustion possess less energy than the original candle.

2.30. Extrapolation Extrapolation is similar to interpretation in that it involves inference. In extrapolation, the inferences are more tenuous and less probable. The learner extends interpretation well beyond the formal bounds of his data, keeping in mind limitations and possible errors. He predicts, implies, and thinks of possible consequences. Extrapolation is not a prediction from a well authenticated principle or a law—this is application. It is prediction from a few events, statements of events, or facts to another, more hypothetical realm.

Predicting the effect of increased salt concentration in an aquarium from the effects of previous increments of salt is an extrapolation. So is the prediction that the moon's surface is weakly radioactive, which is derived from preliminary data about the physical structure of the moon's surface. Extending the known laws of physical and chemical change to the production, transmission, and interaction of nerve impulses in the brain is also an act of extrapolation.

3.00. Application The category of application is at least one level further removed from recall than comprehension is, because that which has been learned must now be tested under new and somewhat different conditions. A student learns that the volume of gas decreases as its pressure increases (temperature remaining constant). He is said to comprehend this principle if he successfully predicts the effect of pressure on the volume of gases. Of course, his success may not be an intellectual success, because he may have arrived at the correct answers by "plugging into" a formula. On the other hand, if he uses this principle to explain why weather balloons expand in volume as they rise, without having previously encountered this explanation, he is obviously making an application. As another example, children readily learn that photosynthesis in green plants occurs in the presence of sunlight. Children who comprehend this principle, and who know that sunlight is a mixture of violet, indigo, blue, green, yellow, orange, and red light, should be able to predict qualitatively what will happen to the food making process in green plants if red, rather than white, light shines on these plants. If they succeed, they have applied their knowledge of photosynthesis and of light.

In order to show comprehension, the student must demonstrate his ability to use a clearly specified abstraction for a particular purpose. To show application, on the other hand, the student does not know that the abstraction is pertinent, because the test situation differs from practice situations. In the first case, recall of the original situation is all that is necessary. In the second case, recall is not sufficient.

In evaluation, it is axiomatic that a learner is not at an operational level unless he successfully applies what he has learned, qualitatively or quantitatively. Success may be shown by explanation, by prediction, or perhaps even by recognition that what has been learned is irrelevant to the problem or application sought. Evaluation of application is difficult, not only because comprehension of knowledge is required, but because it is exceedingly difficult to sense from a child's attempts at application why he is or is not successful. Knowledge of the skills which give direction and strength to this kind of cognitive behavior is not yet sufficient to serve as a guide. It is partly for this reason that so much evaluation is confined to the lesser categories of understanding.

4.00. Analysis Analysis may be defined as the dissection of a problem or event into its logical components, and the description of the relationships, equivalences, hierarchies, and sub-sets of these components. Analysis includes distinguishing between individual facts, separating principles from hypotheses, pointing out conclusions and the steps to these conclusions, identifying implicit and explicit assumptions, and selecting underlying themes. A child who comprehends the meaning of a statement may be unable to attack it logically, to select the important factors, and to recognize the direction in which the argument moves. On the other hand, adequate analysis of a statement is not equivalent to judging its pertinence, accuracy, and validity. In a sense, logical analysis is mechanical, even though it calls for many high-level skills, because insight which is vital for judgment is not required.

4.10. Analysis of elements Analysis of elements is analysis of hypotheses, arguments, and conclusions, which are usually clearly identified in a textbook. In an experimental problem, however, there may be no hypotheses or conclusions to analyze until the class has examined the experimental procedures and the collected data. This sub-category encompasses what Suchman describes as "the analysis of causality," wherein children learn to analyze problems by identifying the kinds of objects they observe, by grouping these objects into systems, and by relating the various states and forms in which the objects and systems coexist to the sequences of events which the children witnessed during their experiments.[7]

Individual events, of course, may be treated as isolated facts. If they are to be understood, however, the aspects which give them meaning must also give meaning to other events. That is, each individual event must be explained by knowledge derived from other sources. Analysis is the process by which the totality of information in the problem is identified so that it may be connected with familiar ideas.

In investigating magnetic interactions, children should be aware of the shapes, sizes, weights, and colors of the magnets and the objects attracted. They should identify the magnet-object attraction system, the temperature, distance between magnet and object, and the attraction of magnet for object and object for magnet, including sequences of movement. They should identify the magnet as the source of the magnetic field, and the object as a preferred pathway for the magnetic field. This is a simple example, but it does indicate the complexity of analysis of elements.

4.20. Analysis of relationships The sub-categories which have been described are by no means sharply defined. They shade indistinguishably into one another, overlapping to such an extent that categorizing a specific behavior as evidence of translation, interpolation, or knowledge of conventions or of criteria is often an act of faith.

In the analysis of relationships, we attempt to clarify the precise association of the elements which have been identified. Have the proper data been collected to test the hypothesis? Is the conclusion such that acceptance or rejection of the hypothesis is necessary? Are the data, conclusions, and arguments of sufficient strength? Which are too trivial to be included? Is the analysis consistent, harmonious, and supportive of the argument? What parts of the data and conclusions are irrelevant? Does the conclusion follow logically from the chain of reasoning? Does the writer contradict himself? Is contradictory evidence known to the reader?

In the pendulum experiment of Chapter 4, does the learner know why the length of the pendulum is a significant variable? The learner must associate the length of the pendulum, its period, and the gravitational acceleration of falling objects, which are the important factors, and simultaneously disregard the mass of the pendulum bob, the material of the bob, and the arc of swing (within limits). Two of the most common confusions of children analyzing relationships occur because they blend the various independent variables, and, without practice, fail to think "if this thing happens, then that thing must happen next." If children know how the flow of an electric current in a wire is related to the voltage, they should be able to infer that current must increase as voltage increases, as long as the resistance in the circuit is unchanged. Children who show this level of scientific maturity have correctly analyzed the relationship of three important variables.

4.30. Analysis of organizational principles It is probable that this sub-category is inapplicable in elementary experimentation, although the separation of the various phases of an experiment into defining the problem, hypothesizing, gathering data, and coming to a conclusion may be an example, if the experiment is analyzed for this purpose. Children who are trained to read for information are often taught to examine the table of contents in order to analyze how the author has divided the content. Is the book a methodical survey of a particular field, or is it merely a potpourri? Is it unified by an underlying theme?

The formal organizational structures of individual chapters, of reports, of projects, and even of motion pictures may be similarly analyzed.

For example, the organizing principle of Chapter 5, "Foundations of the Science Curriculum," is the generality and power of certain related and abstract ideas which collectively comprise the structure of science. In assessing a motion picture, the teacher may ask for a statement of its purpose and of the function of each section. He may point out the special techniques for making various points, and discuss with the class the point of view of the film producer.

The organizational principles of elementary-science textbook series are of interest to prospective teachers. Is the framework of the series the "big ideas of science"? Are these "big ideas" set in an array so that they are periodically reviewed and enlarged? On what basis are the ideas chosen? What is the author's rationale for the ideas presented at each grade level? How are they inter-related? The answer to these questions will emerge from an analysis of the operational principles of these books.

5.00. Synthesis Synthesis is one of the highest forms of behavior in the hierarchy of learning. Synthesis, which may be equated with creativity, is the discovery of likeness, the rearrangement of old ideas, and the incorporation of old or new ideas into a novel structure. This kind of creation, which appears to be a relatively modest combination, is often perilously difficult to achieve. The classical grumble of the great physicist James Clerk Maxwell, when he learned of the invention of the telephone, is an example of how even men of unparalleled creativity may be blind to what hindsight tells them is obvious. Maxwell said, "When at last this little instrument appeared, consisting, as it does, of parts, every one of which is familiar to us, and capable of being put together by an amateur, the disappointment arising from its humble appearance was only partially relieved on finding that it was really able to talk."[8]

Several of the categories previously described require some synthesis. In order to make applications, individual elements must be combined in new ways. In application, however, these elements are known to be related. In true synthesis, the synthesizer finds unsuspected relationships.

No one expects an elementary school child to make truly novel syntheses in science, although he is capable of synthesis in the realm of the arts and literature. Perhaps the closest approach to synthesis in elementary science is to plan an experimental approach to a problem to which the solution is not known, or to propose a scientific explanation.

5.10. Production of a unique communication In this category are included communications such as a written or oral field-trip report in which a child accurately reports on erosional phenomena he has observed and explains them or relates them to what he already knows. A description of a museum trip which is more than a visual catalog is also a unique communication. So too is sharing of unusual experiences which leads to renewed interest and study and to the production of new plans of operation by the children.

5.20. Production of a plan or proposed set of operations Science affords an excellent opportunity for observation of this behavior, which is inherent in Inquiry teaching. Although individual children are sometimes capable of proposing such plans, they are more often the product of small-group or whole-class action, sympathetically guided by the teacher. The value of a plan may be judged by its operational success, although for obvious reasons some plans cannot be tested in the elementary school. A teacher may gather evidence of growth in this realm of behavior by proposing a hypothesis to his group and noting the different procedures advanced to test it. The class may design an apparatus for performing a particular operation, such as weighing objects which are too small to give a reliable reading on the classroom balance or ascertaining the effect of heating confined gases. Unique contributions signify a high level of cognitive strength and creative effort. There is the widest latitude for individuality, because of the high probability that many different sets of intellectual operations will be necessary.

5.30. Derivation of a set of abstract relations The creation of taxonomic keys by which rocks or plants may be classified is a relatively low-level example of this kind of behavior. By discovering similarities and differences, children can devise convenient and logical sorting procedures. The kinetic-molecular theory may also be derived from observation of gaseous diffusion, pressure-volume changes in gases, evaporation, solubility, and change in state of solids, but few elementary school children can derive either the kinetic-molecular theory or a simplified model of it from direct experience without the teacher's encouragement and close ministry.

The formulation and later modification of hypotheses which explain and predict phenomena or events is included in this category. The possibility of looking at experience in more than one way, or the realization that there may be more than one explanation or theory, is still another instance. One of the characteristics of the new sciences, of what is figuratively their "growing edge," is that there are often no theoretical explanations; or, on the other hand, there may be a multitude of hypotheses of various degrees of credibility. The question of the moon's origin is not conclusively settled, nor is there a broadly based theoretical structure to account for the multitude of particles encountered in nuclear physics. It is surely important for children to realize that explanations are sometimes accepted in science because they are more "elegant" or simpler than other explanations, or because they are the best at hand, even though they are not completely correct.

6.00. Evaluation Evaluation is judging in terms of accepted criteria. Judgments are necessary in many of the categories previously described; the difference is that in evaluation the notion of value is introduced. Because of this, evaluation is closely tied to the affective domain, described below. The fact that evaluation is the last category in the cognitive domain does not mean that it is the noblest kind of behavior, nor that it is the ultimate intellectual act. After all, individuals always make judgments, even in so minor an intellectual act as recalling a particular fact. However, there is a vast difference between *opinion*, which is quickly formed on inadequate evidence or unconsciously accepted without serious question, and *judgment*, which is more deliberate and searching.

6.10. Judgments in terms of internal evidence Judgments in terms of internal evidence rely on expressions of logical consistency, the existence of factual errors, the quality of thought, the range of data and of generalizations. In judging experimental evidence, have the errors or possible errors been reported? Is it likely that the same results will be obtained if the experiment were to be repeated? Are there hidden assumptions which invalidate the conclusion? Is the conclusion logically correct?

6.20. Judgments in terms of external criteria In science, the external criteria for evaluating scientific research are well known, and make up the basic evaluational structure of the entire scientific community. For instance, are the experimental results compatible with present theory? Is the work that of a person with an established reputation? Is it adequately sampled and controlled? Is the theory or hypothesis advanced more inclusive or simpler than others? Is it better integrated with other theories? Does it explain more effectively? Has the experimenter examined alternative courses of action? Has he tested every conceivable hypothesis which could invalidate his results, or has he been content to "prove" his hypothesis? Does the hypothesis lead to new knowledge? In Conant's phrase, is it fruitful? To what extent does the author's bias intrude? Does he take into account the pertinent work in his field?

Infusing the desire to make scientific judgments and providing frequent opportunities for judging is essential in elementary science. There is good evidence that children's skills in judging their work and that of their peers can be strengthened. In turn, teachers must learn to judge their own successes and failures as well as those of their students.

The levels of the affective domain[9]

Objectives in science education are often as vaguely phrased as these: "To appreciate the role of science in the progress of mankind"; "To develop a scientific attitude in dealing with problems of everyday life." These objectives and the behavior which they imply are not equivalent to the objectives of the cognitive domain's understanding and knowledge, even though they affect cognitive thinking. "Willingness to receive," for example, will expedite learning at every age level, even though learning can occur without it.

The affective domain is the class of subjective behavior that is dominated by attitudes, emotions, and appreciations. These are the "intangibles," which by common agreement are vital for learning, but which are not often evaluated in science teaching. One explanation for their omission is the unsupported assumption by many scientists and science educators that desirable affective behavior arises mechanically and inevitably out of science content. That is, the student who struggles through a well-organized course in physics which includes one or two hours in the laboratory each week becomes an exemplar of the methodology of science and of all that is good in science. Because this notion is utter nonsense, many of the new programs in science education are permeated by the Inquiry philosophy.

In the literature of affective behavior there is no agreement on the meaning of key words; these words must be defined for this particular analysis. An *attitude* may be regarded as a willingness either to approach or to avoid environmental interactions; *appreciation* is a measure of satisfaction in interacting. Pleasure, dislike, and joy, which are ignored in formal learning, must also be included. It is certainly an important function of science instruction to motivate children so that they will want to know more about their world, will enjoy working with scientific equipment, will like to read science books, and, by looking forward to a scientific problem, will begin to enjoy the reward of autonomous learning.

Teachers want children to establish desirable attitudes, appreciations, and interests, both because they believe that the task of learning will be less arduous for both children and teachers and because learners can create within themselves the operational machinery and self-control that will drive them on. One of the measures of effective instruction is the extent of the children's shift from external to internal motivation.

In a sense, this process is circular and logically suspect, almost as if one could raise himself by his bootstraps. Interest children in learning science! Interest leads to success. From success, an even more potent interest emerges. But this growth does not automatically arise from exposure to the materials of the sciences. The teacher must consciously seek to arouse in children the *desire* to learn. He must realize that he can serve as a model of the behavior he wishes to inculcate.

Evaluation in the affective domain is a formidable task. Evaluative instruments for elementary school science are almost unheard of. Informal observation and judgment by the teacher are the only substantial sources of growth data in this domain. This condensed outline of the elements of the affective domain, along with the accompanying suggestions for observation of behavior, is proposed as an empirical guide for the evaluation of affective behavior.

1.0. Receiving (attending) There are three subcategories within this category; they are given in ascending order.

1.1. Awareness Awareness is assumed to be the lowest level of the affective domain. It is the act of giving attention to some occurrence or phenomenon, even if the occurrence is disliked and avoided. The learner is conscious that something has happened, although he does not pay specific attention to it. This is too primitive a level for most classroom learning. The learner may sense only the gross phenomenon, or some of its interactive components. He figuratively says, "I am aware of it. But I couldn't care less about it."[10]

A child who thinks that science is only for scientists is either unaware of the role of science in modern society, or, if aware, does not care about it. Although the child who is *aware* that other points of view exist may not be willing to credit views which differ from his own, at least he knows they exist. The child who is *aware* of the existence of atoms and molecules may not be able to use molecular motion in explaining the diffusion of ink in water; or he may not care to do this. Awareness and cognition are closely related; ability to recall a principle implies awareness of the principle.

1.2. Willingness to receive Instead of unleavened passiveness, this sub-category implies desire to come into contact with a stimulus, although not necessarily to form a positive prejudgment. The child may be hostile, yet tolerant enough to listen; he does not actively seek out the stimulus. He may be willing to participate in an experiment if asked; he does not volunteer.

Examples of this behavior include tolerance of different points of view, cooperative attitudes in class discussion, participation in discussional give-and-take, and acceptance of new units of study in the classroom. The willing child does not peremptorily reject an activity; he looks forward to participation.

1.3. Selected attention The emphasis in this sub-category is on attending to individual activities and elements rather than to the total setting. This does not mean that the child necessarily wishes to know more, or that positive interest is involved, but rather that he observes at a higher analytical level. The child may neither know the meaning of the significant components of the activity, nor describe them, nor tell what can be done with them.

Skill in observing and in perceiving configurations and relationships are examples. The child who systematically follows a teacher's demonstration, attending to each step in the process, whether or not it is meaningful, is giving selected attention. The child who prefers biographies of scientists or books about space exploration is similarly giving selected attention.

2.1. Acquiescence in responding Attending is apt to be meaningless unless the learner is willing to use that to which he attends. Acquiescence in responding is "higher" than receiving in the affective domain. The learner is expected to comply, willingly or unwillingly, and to follow prescribed rules. Teachers reject forced acquiescence as an important behavioral goal, even though it may occasionally be important (e.g., "You shall not mix chemicals randomly; you shall not experiment at home or in the classroom if there is a possibility of touching powerful electric currents; you shall not handle apparatus roughly"). Students should know the reasons for these rules, and accept the rules because they are reasonable and productive. This implies a higher and more desirable response. But whether behavior is intelligent or not, safety is vital! The child who must continuously be reminded the rules of safety shows unwilling compliance.

2.2. Willingness to respond The child who willingly and voluntarily carries out his assigned tasks need not display an interest in what he is doing, although interest will undoubtedly make his tasks easier to complete. Effective cooperation among children can occur if each wishes to work closely with his peers, but this willingness may come from one or a combination of factors—desire for social approval, teacher insistence, innate interest, self-reward, etc. In the primary and intermediate grades, one of the strengths of science taught with concrete materials is that children become deeply involved and look forward to experimentation, to field trips, and to science "doing."

Children who go voluntarily to the library to borrow science books, who bring in pertinent newspaper clippings, who practice conservation, who are home experimenters, who participate freely in class discussions exemplify this behavior. Teachers often think of willingness as interest, but the two are not necessarily synonymous.

2.3. Satisfaction in response Satisfaction in response should be actively sought by both teachers and students, because it is self-rewarding. A child who enjoys an experiment or takes pleasure in a book about insects is apt to want to know more, to want to strengthen his competence. Traditional modes of learning are often negative, in the sense that children become discouraged or even inhibited. Few children *enjoy* studying textbook science. It has often been said that one of the reasons that science is difficult to teach to older children is that they have become conditioned by their dislike of traditional instruction. Cognitive learning is not necessarily achieved by mere satisfaction in responding. An individual may be intensely interested in a topic without trying to learn much about it, as the controversies which rage about fluoridation or vivisection illustrate. Deep interest and excessive emotion do not necessarily promote knowledge of the chemistry of fluoridation or the importance of vivisection for medical research.

Pertinent examples of satisfaction in response are plentiful. Some have been mentioned previously. Additional examples are enjoyment in observing and identifying birds, in collecting rocks and minerals, and in building model airplanes and learning why they fly.

3.0. Valuing It is clear that these affective behaviors are not distinctly different from each other or from some cognitive behaviors. This blending is especially evident in the realm of valuing. To give value to some phenomenon, attribute, or mode of acting is to endow it with worth, so that even if an individual chooses not to act on it, he respects it and its reasons for existing. This is the realm of the scientific attributes of accuracy, elegance, truth, and simplicity—the scientific values which Bronowski affirmed so expressively in *Science and Human Values.*[11]

3.1. Acceptance of a value Acceptance of a value is one of the lower levels in the valuing hierarchy, because it does not require firm commitment. It is a position which is likely to change. Individuals may occasionally accept the traditional values of science, yet violate these standards of behavior despite the disapproval of the scientific community and the ease with which deviations may be detected. For example, Paul Kammerer, a noted biologist, once exhibited several artificially altered salamanders in an attempt to prove that acquired characteristics can be inherited. In 1925, Kammerer was rewarded with a professorship at the University of Moscow, because Communist doctrine at that time leaned heavily on Lamarckian evolution. He commited suicide shortly thereafter, when he realized that the scientific world knew that he had rejected the accepted norms of scientific behavior.

The child who says that he would like to become a scientist gives evidence of one kind of value acceptance. If, in addition, he reads widely, collects, experiments at home, and persistently seeks to help his teacher in preparing science activities, he is probably at a higher level of valuing than simple uncommitted acceptance. If he is willing to listen to evidence and to wait to gather evidence before coming to an unshakable conclusion, he shows signs of accepting the scientific canon of adequate evidence. The child who accepts the values of Inquiry techniques as a class procedure is also at this level, but this acceptance will occur only if he derives some satisfaction and challenge from these values.

3.2-3.3. Preference for a value; commitment to a value In this combined sub-category, the learner is impelled to action. If he truly believes in conservation, he will act appropriately. He will *not* pick protected plants, deface a nature center, or carve his initials on a tree. He pursues this faith in conservation, preferring it to contradictory beliefs. He invests his own effort and time in its active realization, and is loyal to it, defending it against others if necessary. The child who volunteers to complete a project or to plan an experiment because he genuinely wants to learn its outcome, and who believes in the experimental approach, is committed to scientific values. He rejects superstition and the intervention of supernatural causation, which are not based on reason and objective evidence. He is committed to the criteria of scientific evidence and validity. These are not the kinds of behavior which arise quickly and naturally in the classroom. The child's attitude to his world is so conditioned by his upbringing and social environment that teachers will settle for reasonable progress toward willing acceptance and commitment to scientific values.

4.0. Organization Science instruction seeks to build a value system, not a succession of discrete beliefs and attitudes. It is possible for children to grow in accepting and preferring certain values, even though their growth is necessarily incomplete. It is much more difficult for them to conceptualize these values by analytical and synthetic techniques, and to acquire a rational system for making choices. The refusal of science to provide a readymade system may lead to undesirable choices, perhaps to avoidance of science. Children may espouse the "one true doctrine" if science is taught as doctrine; teaching by indoctrination has occasionally been urged, so that children will think that science is "good." Yet it would be a serious error to commit the very sins of commission and omission which are anathema to science in the *name* of science. Therefore, teachers should try to give children some experience in evaluating the adequacy of their belief systems.

4.1. Conceptualization of a value In addition to maintaining particular beliefs, the learner should be able to compare these beliefs with others which he holds or which he may formulate. These values become part of a consciously maintained conceptual structure. In order to inter-relate these values, the learner must clarify his understanding, either intuitively or logically. He must be able to think about it and to assess its relevance.

The learner should be able to express his belief that scientific ideas are directly or indirectly connected with a real world; that the atom, even though it is a theoretical model, is represented in the physical world by a particle which shows the kinds of behavior illustrated by the model. He should be able to explain, at least to himself, why the pursuit of science depends on accurate observation, in which the observer subordinates his own biases and interests to the greater good of honesty and dependability.

4.2. Organization of a value system Once conceptualization of individual values takes place, it is desirable for these values to be harmonized. One hypothetical cause of mental illness is that some individuals have not attained this consistent, dynamically integrated order. The dissonance which they encounter in living is sufficient to impair normal mental health. Mental illness may occur if individuals hold non-harmonized values so strongly that they cannot be resolved without internal conflict.

The kinds of behavior included in this sub-category are illustrated by class discussions in which the cost and the benefit to society of more vigorous anti-pollution measures are weighed or the benefits and evils of nuclear energy are evaluated, and by the acceptance of cooperative work in small-class groups which conflicts with individual action. In one of the highest levels of this sub-category, the learner may answer questions like these: "Why is it important for every citizen to know what science is? What are the aims of scientists? What changes for good or ill has science caused in our lives?"

5.0. Characterization by a value or value complex For this category to be meaningful in science instruction, the learner must possess a value system which effectively controls his behavior. This, one of the loftiest levels of valuing, may be inappropriate for the elementary school. Ten-year-olds have not consciously formulated a philosophy of life; this is a task for a lifetime. The analysis which follows is intended to suggest directions of desirable growth; it is not behavior to be expected of school children, although children do grow significantly in this as in every other affective category.

5.1. Generalized set This sub-category of behavior has been defined as "a basic orientation which enables the individual to reduce and order the complex world about him and to act consistently and effectively in it."[12] Broadly speaking, it is the individual's frame of reference for meeting affective situations. This is the behavior exemplified by "the scientific attitude," which is an entire complex of skills, understanding, attitude, belief, and behavior. The person who judges situations by pertinent facts, issues, intentions, and results possesses one kind of "generalized set." He is rationally consistent. The scientist who, at whatever anguish, admits to himself that he has overlooked a point which invalidates a pet hypothesis vividly illustrates a generalized set. It is unthinkable for him to ignore this error! Lord Lister once said, "Next to the promulgation of truth, the best thing I can conceive that a man can do is the recantation of a public error."[13]

5.2. Characterization Characterization is regarded as the highest level of affective behavior, because it embraces the greatest range of behavioral objectives—the individual's complete world view. Because it is so abstract and personal, it does not fall within the domain of elementary school evaluation. Nevertheless, this excerpt from John W. Gardner's book, *Excellence: Can We Be Equal and Excellent Too?* is pertinent:[14]

> To win our deepest respect the individual most both find himself and lose himself. This is not so contradictory as it sounds. We respect the man who places himself at the service of values which transcend his own individuality—the values of his profession, his people, his heritage, and above all the religious and moral values which nourished the ideal of individual fulfillment in the first place. But this "gift of himself" only wins our admiration if the giver has achieved a mature individuality and if the act of giving does not involve an irreparable crippling of that individuality. We cannot admire faceless, mindless servants of The State, of The Cause, of The Organization who were never mature individuals and who have sacrificed all individuality to the Corporate Good.

The psychomotor domain

The *psychomotor domain* in science is a region of darkness and doubt, an unexplored wilderness which offers little of promise in the teaching of science. The *psychomotor domain* is the realm of motor skills, physical development, and neuro-muscular coordination. What have these non-cognitive, non-affective patterns of behavior to do with science learning? Should teachers launch immediate remedial action if an awkward child takes five times longer to connect a dry cell than another child, or if, on a field trip, he is never able to catch a frog or a butterfly? Some children *are* awkward; girls tend to be less skilled mechanically than boys for reasons which are not at all psychomotor. Many children are inferior draftsmen; they are sometimes unable to plot a curve on a graph because of a neuromuscular problem. These deficiencies are not problems of science teaching, although the teacher should be aware that they exist and that they may be symptomatic of a generally low level of psychomotor function.

Coordination and speed in elementary science are not significant behavioral objectives. Delicate manipulation is unimportant, because appropriate experiments for younger children are well within the physical capacities of school children. It may be true that "practice makes perfect," but the duration of manipulative tasks in elementary science is too short for the effect of practice to show itself. The tasks themselves are not worthy of extended practice.

Many scientists are indifferent experimenters, lacking the insights and skills which characterize experimental scientists. Indeed, in the field of high-energy physics, theoretical and experimental physics are sharply separated. Physicists are not usually adept in each domain. Manipulative skill is undoubtedly advantageous for children, but its order of priority is surely low, and it is doubtful that the teacher should take on this additional burden in teaching elementary science.

Techniques of evaluation

This lengthy catalog of evaluative behaviors is a sample of the evidence which teachers must seek. It is a guide to the kinds of actions which reflect cognitive and affective learning. It is not expected that teachers will find every kind of behavior. This task is beyond the capacity of the most gifted teacher, even if assisted by every resource of the educational establishment. The teacher must select those kinds of behavior which are most important to him. To assist the teacher to use these suggestions most effectively, there are a number of evaluative techniques for gathering behavioral evidence of achievement. Whatever the techniques, evaluation must truly be continuous and cumulative. What we seek is detailed knowledge of behavioral change, a quest which is complicated because dramatic behavioral changes rarely occur.

Gathering this knowledge will challenge the most keen and assiduous teacher. The wise observer is a skilled listener who allows little to go by without a mental self-memo. He is alert during the classroom discussions, sharing periods, experiments, and demonstrations, as well as during the children's free time, as much for signs of standing still or of regression as for signs of progress to new and more desirable patterns. There are a number of questions which he will want to answer.

Who participates in the different activities, and what is the nature of this participation? Are the doers, the movers, the leaders a small, relatively fixed group? Which children take part in discussions, but never in sharing period? Which shun science, participating instead in social studies or arithmetic? Is the child just a listener—perhaps an active listener, but never more than that? Identifying active and inactive children as individuals and as group members is a necessary part of his task. How efficiently does each child begin his work? Does he move ahead without wasting time? Is he a self-starter? No teacher expects children to be self-regulating in all elementary school endeavors, but in what respects are they independent learners? Must the child be directed at every step? Does he spring ahead at the beginning of each new enterprise, but fall back soon?

What is the quality of the child's observations? Quality of observations refers to the accuracy and inclusiveness with which the child sees and hears. How much does the child miss? Does he see unusual configurations, images, or relationships which others fail to see? Is he quick to see what is there? In watching demonstrations and experiments, does he carefully follow the successive steps and record the results?

Are his explanations factual, without teleology, anthropomorphism, or animism? Does he make statements such as these: "The sun is alive because it comes back every morning." "The viceroy and monarch butterflies are alike so that the viceroy may escape birds that would otherwise eat him." *Are his explanations phrased in causal terms,* in which dependent and independent variables are included in some theoretical context? This is explanation on a high level. On a less abstract level, can the child think like this: "If this is true, then that must also be true." Can he explain the rise of water in a footprint in damp soil by referring to inter-molecular forces? Does he state the relevant conditions of a phenomenon or event?

Are his statements clearly worded, or are they so vague and diffuse that it is impossible to decide whether or not he understands either what has happened, or why it happened? If the latter, is this vagueness the result of the child's inability to express himself? Is it because he is not identifying specific individual events, or because he has not established the conditions under which the event takes place? Perhaps he is unable to separate the totality of the experience into its parts.

Are his questions precise and unambiguous? Are they operationally phrased so that their meaning is clear and the direction in which answers are to be sought is implied by the question? Does he try to sort out objects and functions, the conditions under which they exist, the systems into which they are grouped, and the sequence of events? Does he ask questions about problems which interest him? Does he ask questions which seek the reasons for a procedure or which search for ways of eliminating discrepancies between expectation and occurrence? Or are his questions frivolous, cunningly contrived to waste time and to divert the teacher and the class from their course of action?

Are his reasons or hypotheses logical, or are they mere guesses? To what extent are his guesses profitable? Is he naturally intuitive, able by some gift of insight to move to the heart of the problem? The cognitive styles of children vary greatly, and some bright children ignore logical analysis and jump to premature conclusions. Is this such a child?

Does he restrict his comments and questions to relevant points, to items and incidents which should reasonably be included, or are his comments and questions precisely worded, yet irrelevant? Has he missed important ideas? Is he verbose, straying quickly from the topic? Does he oversimplify, seeking single causes of complex phenomena, or neglecting to maintain experimental controls?

Is he aware of the existence of the assumptions which affect every phase of his daily thinking? Does he accept the importance of isolating and analyzing the assumptions on which the quality of his scientific thinking must depend?

Does he hypothesize? Are his hypotheses pertinent, even though they may not be correct? Are they reasonable? Once he formulates a hypothesis, is he able to devise ways to test it, to evaluate its worth? This skill, if skill it is, is not a philosopher's stone which will magically make the learner a scientist. The long history of science testifies to the fact that the formation and testing of hypotheses has always been the standard which separates the creative from the non-creative scientist, the producer of science from the user of science. The evaluation of hypothesizing is a strikingly complex, almost unexplored aspect of science education. For this reason, the teacher's evaluation of the child's struggle to form and to test hypotheses must be charitable and generous.

How well does the child interpret data and find meaningful relationships, assuming that they exist? Is he aware of the boundaries of the problem and the limitations of his techniques and apparatus? Has he sufficient skill in computation and in graphing to interpret data?

Can he tease the plausible inferences out of these data? For example, if moist iron nails consistently rust more quickly than dry iron nails, does he conclude that rusting will probably slow down or cease if iron nails and presumably other iron objects of the same composition, are dried?

Can he predict certain inevitable consequences of laws, principles, and conclusions? For example, knowing the laws of vibrating strings, can he explain how the pitch of a violin string changes as its length is changed? Knowing that many plants selectively absorb and concentrate minerals from the soil, can he foresee how the distribution of plants may indicate the presence of certain minerals? No teacher expects the intuitive leap which the great scientist makes as he boldly moves far beyond the limits of his information. Children are just beginning to gain a foothold on science. What *is* important is that the child begin to make progress in these aspects of science learning. Has he begun to make predictions? Are they justified according to the logic of the situation, even though they may eventually turn out to be wrong? In the absence of teaching which boldly and consistently seeks to strengthen these abilities, little positive growth is likely to occur.

What is he interested in? What is he *really* interested in? Does he consistently pursue these interests? Does he vacillate, jumping from superficial interest to superficial interest? Is his interest so strong that he turns to reference sources for more information? Does he participate in out-of-school activities in which science interests are likely to be fulfilled? Does he concentrate on activities in which his strengths nurture his interests?

Can he read for comprehension, locate source material, take notes, and summarize? Each of these phrases is a deceptively innocent condensation of a multitude of lesser, but no less important, sub-skills, understandings, interests, techniques, and psychomotor aptitudes. In a textbook such as this, it is impossible to prescribe appropriate diagnostic and remedial techniques for these reading skills, despite their relevance both for learning and liking science.

Is his physical coordination good, or is he clumsy and awkward in manipulating apparatus and performing experiments? Is he accident-prone? Are his disastrous manipulations caused by not thinking through the possible outcomes of his course of action, or by impulsiveness and haste? Carelessness may mean only that he made three unnecessary errors in arithmetic, which he easily rationalizes away with the comforting thought that he still knows how to do the problems. In science, however, carelessness or impulsiveness may destroy an experiment on which many children have labored. The group which keeps careful records can identify the child who forgets to water germinating seeds, or who inaccurately records the period of the pendulum. Carelessness is a way of life with some children, and remedial action is difficult under normal classroom conditions.

Is the child sufficiently aware of his own successes and failures, his weaknesses and strengths, to reinforce success and to attend to difficulties? Does he seek feedback, so as to minimize future errors? In many children, the urge to reorganize behavior in order to eliminate mistakes is feeble, perhaps because being wrong and engaging in undesirable behavior are unimportant to them. Teachers must demonstrate to children the power of appropriate behaviorial changes to enhance effective science thinking. Teachers should point out how helpful feedback is to the class and to the individual child, presenting specific examples to show how errors are convertible into future strengths. One condition for successfully reorganizing behavior is immediate recognition of errors. Immediacy is one of the strengths of programmed instruction. The learner becomes aware almost instantly of his mistakes and successes, and therefore pushes himself through the series of steps in the program to bring about "correct" learning. At present, however, there is no way to program this kind of error correction with the higher kinds of learning, such as hypothesizing, inferring, recognizing hidden assumptions, separating out variables, and coming to reasonable conclusions. There are, unfortunately, few tested techniques for creating feedback other than that of programmed learning.

Can the child follow directions? One of the most common complaints, both in and out of school, is that a child is either unable or unwilling to do as he is directed, even when directions are simple and clear-cut. However, the directions may not be as clear as the teacher imagines them to be. The child may encounter reading and comprehension difficulties; or he may simply be impatient, assuming that the task is so simple that he will be able to figure it out in the course of the activity. Even with Inquiry, in which lengthy directions are avoided, there must be rules, procedures, and approaches for increasing success. The child who disregards these rules interferes with classwork and adds to its difficulty both for himself and for others. If the underlying causes of disregard are psychological or social, it may be unreasonable to expect much improvement in the classroom.

Is the child able to work cooperatively? Inquiry teaching relies on small-group investigations, in which each member of the group contributes his talent and insight. Children must come to realize that group success depends on the positive contributions of each working member. The child who is cooperative accepts willingly the rules for classroom investigation which come out of joint teacher-student discussion. An occasional child is much more effective by himself—thinking and performing more efficiently alone than in a group. But he should nevertheless have some experience with other children, because of the refinement of ideas and the valuable criticism which arise from group work. The child who shrinks from the give-and-take of discussion, either in a small group or in class, is missing out on an effective social tool for better thinking and learning.

The tape recorder

The tape recorder is one of the most valuable mechanical aids for evaluation—both for self-evaluation by children and teacher and for evaluation of children by the teacher. Children quickly accept the tape recorder if it is presented and used as a tool to help them learn science, rather than an electronic spy. Novelty is a recognized stimulus to learning—the excitement engendered by tape recording is in itself a sound reason for its evaluative use.

Replaying the tape after a discussion in the classroom will be a revelation to the children, who are not aware of how the teacher has focused their discussion on a particular theme. As they listen, they will begin to realize the misconceptions, erroneous information, and unwarranted statements they have hurled at one another and at the teacher, and how the discussion has been monopolized by a few children. The teacher can stop the tape at any time to ask if children choose to revise their statements, to point out dubious assertions and illogical thinking, or to call for criticism of what was said. The tape recorder provides uniquely for more-or-less immediate feedback; the repetition which occurs, although not the important reason for taping, is also valuable. With this instrument, the teacher may, at his leisure, assess the progress which his children are making and plan necessary remedial action. He can analyze the contributions of each child and the pertinent information recorded. This evaluation, however, will probably be somewhat less important than the postmortems in which teacher and children cooperatively study the tapes.

Other observational techniques

Specialists in evaluation have suggested a number of valuable techniques. Unfortunately, these techniques are time-consuming and laborious to prepare and to use. The elementary school teacher is a busy, hard-pressed individual; the most highly motivated and professionally oriented teacher will find little time for formal record keeping. Even if time were available, it is often exceedingly difficult to decide whether a particular behavior exemplifies inference, assumption, or questioning. How can a busy teacher find the time in the midst of an active science lesson to make these decisions for even one child and to fill in a check sheet listing appropriate behavior? She can, however, decide quickly that behavior X is an example of good or bad scientific thought, and file this as a mental record. Behavior analysis in depth can occur most easily in the course of tape replayings, either with class participation or after school.

Although it is most desirable for the teacher to keep a running record of the daily cognitive and affective behavior of his students, it is not at all easy to do, for the reasons cited above. In all probability, the teacher will be forced to rely to a greater or lesser extent on written tests devised to isolate and assess these abilities, but, unfortunately, these tests are somewhat primitive at the present time. Team teaching in the elementary schools may make the task of record keeping somewhat easier, because the team usually includes a teacher's aide, who is the recorder. At present, anecdotal records, interviews, and intensive observation of individuals are as impractical as they are desirable in filling in the picture, which must otherwise be painted with rough, informal strokes. For problem children, detailed records and the widest possible range of information will be necessary. The teacher will always "interview" children, for this is precisely what he does as he stops to chat with a child to see how he is getting on and to question him on his problems. However, if the child believes that whatever he says will be held against him, he is much more likely to give stereotyped answers or to withdraw into silence.

Special observational tools are best left to specialists in the schools, who have the required time and skills. The classroom teacher, on the other hand, is in the best position to gain a valid insight into his children's progress from informal observation of their everyday business.

Testing

Despite the advantages of an observational approach to evaluation, there is much to be said for the written or oral test. There is the "assurance" that a letter grade supplies a more meaningful measurement. The general practice of schools, less marked in the elementary than in the secondary schools, is to mark on proficiency on written tests.

Testing is the process of using evaluative devices to obtain quantitative measures of ability or knowledge. However, there is *nothing* more meaningless than a single raw score! Let us assume, for example, that a child receives a mark of 75 percent on a paper-and-pencil test on magnetism. This does not mean that the child knows three-quarters of what the teacher thinks is significant; it does mean that on this particular sampling of test items, this child answered three-quarters of the items "correctly." For the child, this may be either excellent or inferior. Whether the test is teacher-made or standardized, the teacher alone is in the position to make a valid judgment. The fact that a child is in the thirtieth percentile on a national examination means little, because comparison of norms is the most trivial aspect of test interpretation. The questions on the examination may be irrelevant; they may be too difficult, too easy, or even invalid because they do not test what they are supposed to test.

Testing in elementary science is important, but it is not more valuable than the evidence which the teacher continually gathers from informal observation. It *is* possible to devise tests which examine how the child thinks, how he infers, reasons, analyzes, and concludes. Tests may also motivate children who are susceptible to such motivation. On the other hand, children who are overanxious, who are poor readers or writers, or who are indifferent are likely to be penalized. It is almost impossible to construct a valid paper-and-pencil test of experimental ability, because actual experimentation is far different from talking about it. Paper-and-pencil tests are at present limited to certain aspects of affective cognitive learning. And, unfortunately, tests of affective behavior are noteworthy for their general lack of validity and reliability.

Informal paper-and-pencil testing

Criticism of conventional paper-and-pencil testing in science is almost cruelly gratuitous, because the shortcomings are so obvious. Informal tests, whether constructed or adapted by teachers for their own classes, are often unreliable; inferior items have not been weeded out, nor have these tests been item-analyzed. The most serious criticism of informal paper-and-pencil testing is that insufficient time is taken to prepare enough fair, unambiguous, and clear questions to make judgment possible.

All too frequently, the important goal of the test is to find out how much each child can recall. Whether or not the test is short-answer, fill-in, matching, true-false, or multiple-choice, it tends to emphasize questions which are conveniently answered from memory: "Name the planets in order from the sun." "A piece of iron which attracts one end of a piece of iron, and repels the other end is called a ________." "All insects have ________ legs." Concentration on recall is understandable for two reasons: first, knowledge of factual material has always been the functional aim of elementary-science instruction; second, it is unlikely that the classroom teacher can devise valid test items for measuring the higher cognitive skills. Nevertheless, to make this objective the sole goal of informal (or formal) testing is to make a mockery of evaluation.

Directions are sometimes so confusing that children lose time in seeking clarification, and perhaps never resolve their confusions. In addition, many test items are so poorly written that children are unable to decipher the teacher's intent. Questions may be ambiguous. Some of the answers, on the other hand, are obvious because leading words, or inadvertent clues are included. Children who are "test-wise" know that a long statement is likely to be correct, and that questions with an "always" or "usually" are likely to be incorrect.

If the teacher seeks to learn how well children can infer, recognize assumptions, sort out variables, and keep factors constant, she must write specific questions for this purpose. One of the most telling criticisms of elementary-science tests is that questions are often irrelevant to the behavior sought. This, of course, is not unexpected, because it is difficult to write such questions for elementary school children.

These tests rarely include enough items written about a single ability or item of knowledge to diagnose strengths and weaknesses; that is, these tests are rarely constructed to serve as diagnostic instruments. In any one test, only one or two questions are written for each concept. For example, a test on "why objects float" includes only one question on density. It is the height of irresponsibility to conclude from this one question that the child either does or does not understand density. Simple errors of reading or of interpretation may be responsible for error, yet there is no way of finding the real reason.

At best, interpretation of tests is time-consuming; yet the teacher should be able to tell the child *why* he is wrong. Is it because he does not know that density depends on both volume and weight? Because he does not understand the difference between density and volume? Because he does not know that the density of water is 62.4 pounds/cubic foot? Because he is unable to visualize what pounds/cubic foot means? Because he does not realize that as long as the volume of an object remains the same, despite changes in form, its density is constant?

In skill and content fields, such as reading and arithmetic, great progress has been made with diagnostic tests, which provide feedback to the child and to the teacher. Diagnostic tests are almost unknown in elementary science.

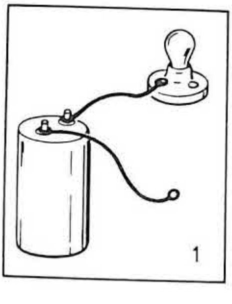
Picture tests

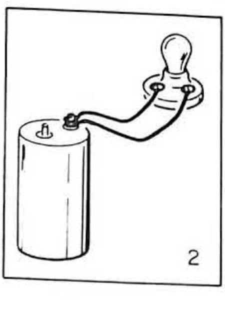
By and large, paper-and-pencil testing is unprofitable in the primary grades, because children are not yet sufficiently skilled in reading and in interpreting questions which probe the higher cognitive processes. For this reason, science tests should be infrequent, perhaps given more to familiarize children with test-taking procedures and to prepare them for testing in the upper grades than to act as evaluative instruments.

An intriguing variation of paper-and-pencil testing for younger children is the picture test, which minimizes reading and verbal skills. A picture test is limited only by the ingenuity of the teacher. The reason for using pictures, either drawings by the teacher or illustrations clipped from a periodical, is to avoid the ambiguities and confusions of written matter. The picture test is desirable, however, only if the questions are effective in assessing modes of thinking.

Some examples of picture-test items are given below:[15]

Directions: Mark an X across the picture that shows a complete circuit.


1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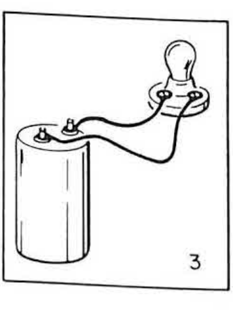
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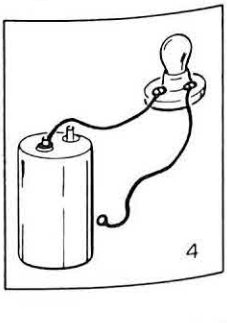
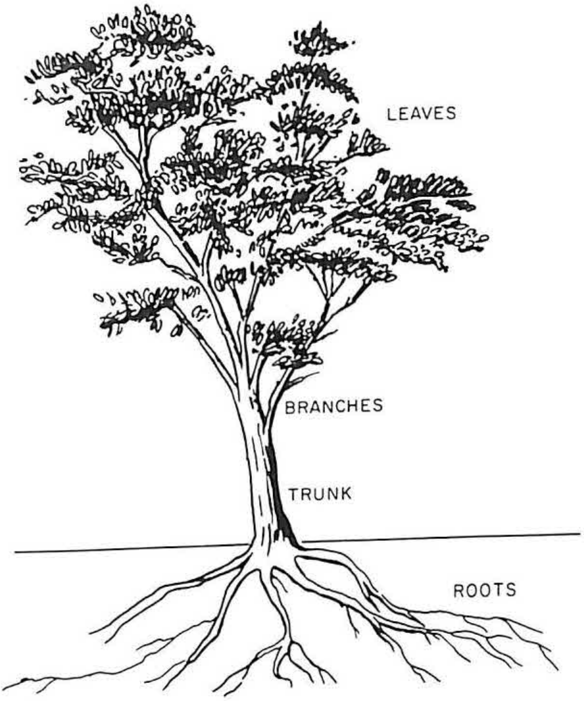
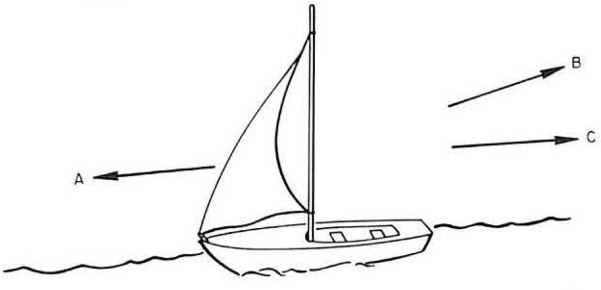

4

Directions: Here is a picture of a tree with names of some of its parts printed on it. Use these names to complete the statements about the tree.



1. The food for the tree is made in the_______.
2. The tree is held in the ground by the_______.
3. Water is taken into the tree through the_______.
4. The sap is carried to the branches through the_______.
5. The food for the tree is stored in the_______.

Directions: Look carefully at this picture of a sailboat being moved by the wind. There are two statements about the boat listed below. Mark an X across the word which makes each statement true.



1. This boat will move because the wind is pushing the ________.
sail water air

2. This boat will move toward____.
A B C

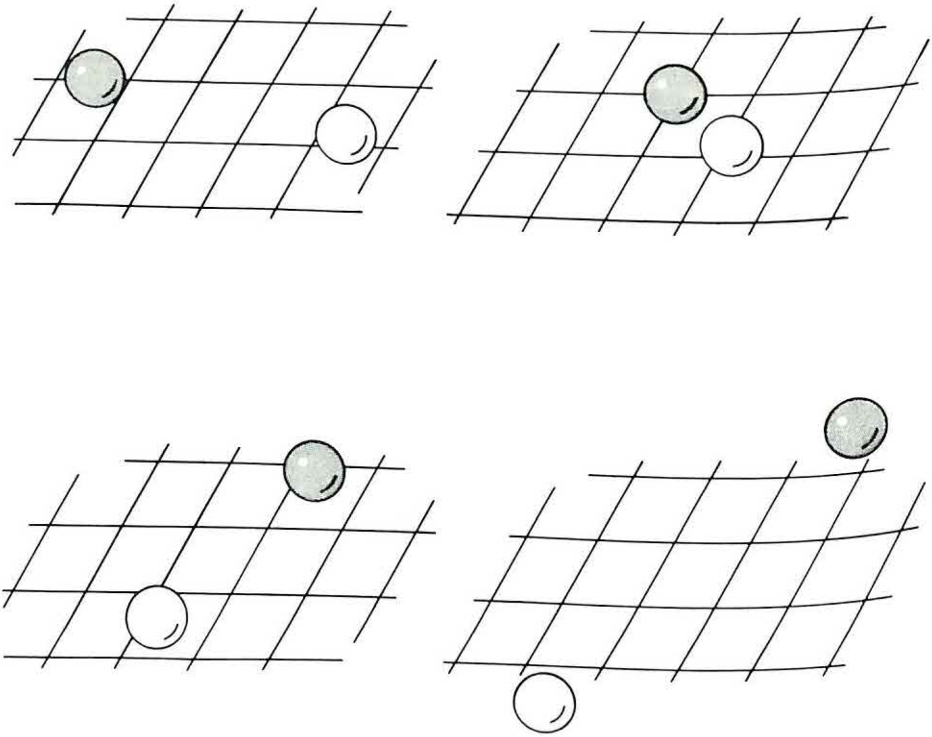
Chapter eleven

These questions have been used with some success in grades ranging from first to third. Whether or not directions and answers should be read by the teacher to the class depends on how well the class reads.

These questions do not probe deeply into the kinds of learning which children exhibit. The first item is a paper-and-pencil laboratory exercise. The task is to apply the information that in a complete circuit which includes a bulb and dry cell, one wire runs from the positive pole of the dry cell to the bulb and a second wire runs from the negative pole of the dry cell to the bulb. For some children, this question will recall what has already been studied, either in the textbook or in direct manipulation of electric circuits. Other children, however, will analyze each picture to identify the elements and their relationships, and answer the question by applying the principle or whatever variation of it they have formulated. A number of the cognitive behaviors previously described are presumably involved in giving a thoughtful answer.

The second item is almost entirely recall, although the correlation of graphically represented structures with function raises the level of thought. The third item requires analysis of the picture elements, so as to relate the bellying sail to wind direction and to separate the irrele-

A

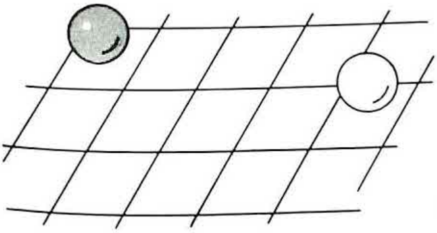


vant directions, B and C, from the logically necessary direction, A. Only children who have had sailboat experience will be prepared to answer the question from memory alone.

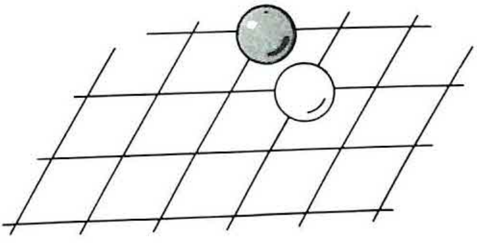
Another example of a picture test is adapted from *Interaction and Systems*, an experimental primary-grade textbook published by the Science Curriculum Improvement Study.[16] These pages confront children who have had much direct experience in identifying objects, interactions, and systems with the following task:

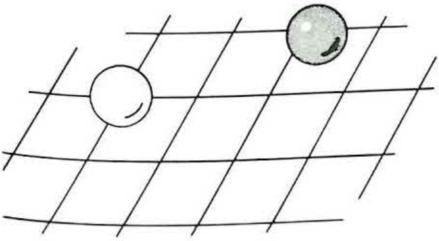
> Here are picture stories of two experiments. The black croquet ball and the white croquet ball are the objects in the experiments.
>
> Did the objects interact in experiment A? ______
>
> Did the objects interact in experiment B? ______

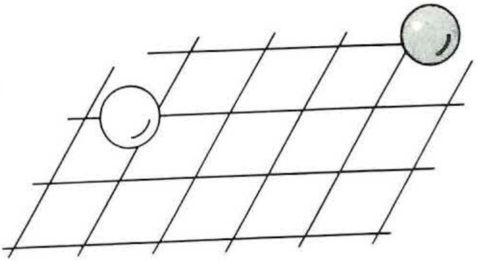
It is possible to convert the last question to multiple-choice form so that children can mark the correct choice or choices as the question is read to them.



B

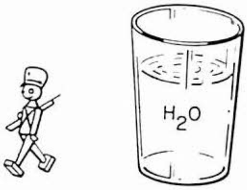


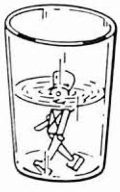


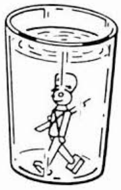


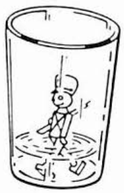
The following examples have been used with some success with first-, second-, and third-grade children:

Directions: Mark an X on the jar of water which shows what happens to the water level in the first glass when the toy soldier is put into it.

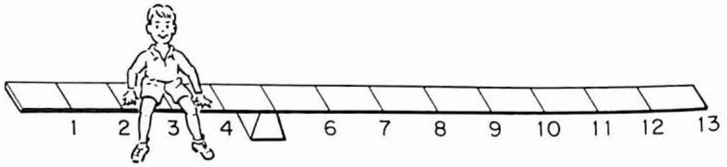








Directions: This seesaw is longer on one end than on the other. Let us say that you sit where the boy is sitting in the picture. Where should another boy who weighs as much as you do have to sit so that the seesaw balances? Mark the place with an X.



Both questions are open to criticism in that they may be answered by simple recall. They demand, at most, ability to apply certain principles of science to situations which may not be very different from the contexts in which these principles were first learned. The seesaw question is likely to be new, because the seesaw arms are not of equal length, and the child must be aware of the effect of the extra length on the right-hand side.

Picture tests are good choices for paper-and-pencil testing, despite the difficulty of writing questions which are comprehensible to younger children. All too often, picture tests are nomenclatural in intent and function and rarely assess the higher cognitive behaviors. They are not, however, *limited* to testing recall.

Directions and supplementary information will be more effective if the test is projected from a transparency by an overhead projector. Not only is the teacher better able to direct her children, but the children can quickly correct their own papers when discussing their answers in class.

Essay and restricted-answer tests

Essay tests are potentially the richest sources for appraising the quality of children's thinking. There is no doubt that essay examinations can reveal how well children analyze problem situations, derive inferences and generalizations from carefully selected data, and assess hypotheses. Unfortunately, children rarely command the writing skills and the analytical abilities which are necessary for fruitful essay testing.

Despite this severe developmental limitation, children in the intermediate grades should begin as soon as possible to write essay responses, not only because writing improves with guided practice, but because children will be better prepared for the writing tasks of the higher grades. Writing answers to essay questions is an art which must be acquired. Questions should be so precisely phrased that children need not wander far afield in search of nebulous words to answer a nebulous question. Essay questions should not be questions which are easily rewritten as objective test items. Questions such as "List the names of the planets in order from the earth, and identify each as larger than, smaller than, or about the same size as the earth," and "When the sun shines on the north pole, what season is it in the northern part of the world?" are not designed to elicit reflective thinking, and are better incorporated into fill-in, true-false, or multiple-choice items. On the other hand, such broad, diffuse questions as "What is gravity?" and "What effect do the changing seasons have on our way of life?" are also to be shunned. There is no answer to the first question, whereas there is not likely to be enough time to answer the second. These questions may be sharpened as follows: "What are some of the things which happen in nature that lead us to believe in gravitational force?" and "What effect does the change from fall to winter have on your use of electricity at home?"

Essay examinations are well adapted (if properly written) to assessing a youngster's ability to analyze a new, perhaps more complex, situation than he has previously encountered. The reader can follow the child's unique quality of thought and the way in which he puts ideas together; he can gauge the child's logical capacity and the degree to which the child responds intuitively. These aspects of the essay test, which fall into the evaluation sub-category 5.10, "Production of a unique communication," are its strengths. Objective testing has not yet demonstrated that it can come to grips with this kind of synthesis of multiple abilities and ideas.

Despite the obvious value of teacher-prepared scoring guides for marking essay papers, the teacher must always guard against rigidity, which leaves no room for unexpected ideas and bright insights. If a scoring guide is used, points for originality as well as for relevance of facts, logical inference, and sound conclusions will extend its scope. The teacher should accept the essay test as a device by which children can escape from the conformity of stereotyped and memorized answers.

Children are much more likely to accept restricted-answer essay tests, because such tests reduce the inevitable frustrations that children encounter in organizing thought patterns at length and in coping with the sheer mechanics of writing. Questions in restricted-answer essay tests set specific tasks, and may be answered in a few lines or paragraphs. These questions should not be so worded that memory will carry the child through.

Objective testing

In striking contrast with essay examinations, which permit some element of freedom, objective examinations are either "right" or "wrong." Teacher judgment is by no means diminished, however, because the teacher must decide which precise bits of information and skills to test, and how to phrase the questions to fit his own objectives and curricular stresses. The form of the objective test chosen – completion (which is not necessarily objective), multiple-choice, matching, or true-false – is a subjective judgment, and, at the close of the examination, he must decide what the scores mean. Is the arithmetic mean to be the starting point? If the mean is high, does the child who is right on three-quarters of the items fail? Decisions like these are difficult to justify for a class and for the individual children in the class. Instead of a mark to be recorded beside each name, the test should be squeezed for all the information it can supply on the progress or lack of progress of individuals and for the feedback for relearning which it contains.

Good objective-test items which probe the higher cognitive behaviors are difficult to formulate. Completion tests, which usually attempt to minimize student guessing, inevitably require some teacher judgment in evaluating the correctness of the answers. An exceptionally well-informed or creative child may come up with a completely unexpected answer. Objective tests almost always imply that *one* and *only* one answer is correct, an expectation which is constricting and unrealistic. True-false items are frequently ambiguous, because they are only relatively true or false and are susceptible to informed guessing. Questions often give contextual clues, such as key words, from which answers may be extracted without knowing the specific information sought. Because of these restrictions, true-false questions are almost always narrowly limited to factual items and, in general, are inappropriate for the teaching of science by Inquiry.

Multiple-choice tests are more versatile, in that the higher cognitive and affective behaviors may be sampled. For example, "best answer" questions demand that judgments be made, although memory may still be sufficient for the proper answer. To construct a five-item question with one and only one indisputably correct choice is a Herculean intellectual task. To write the other four choices, the so-called "distractors," so that they are reasonable is no easier. As a result, test items are often a series of true-false questions disguised as a multiple-choice test. For want of a sufficient number of distractors, teachers sometimes use such choices as "none of these" or "the right answer is not given." There is an advantage to their use, but unless questions are occasionally worded so that "none of these" is right, children quickly learn to disregard them, and thus increase the probability of guessing correctly.

For the intermediate grades, the maximum number of choices in each multiple-choice question should be four, because most children are unable to handle five alternatives simultaneously. Multiple-choice tests are more or less impractical in the primary grades, because of time and reading limitations, although with practice second and third graders are able to manage three-choice items.

In general, teacher-constructed objective tests in the intermediate grades are not valid instruments for evaluating the higher cognitive behaviors which are so important in science, because the questions and choices are complex and because it is almost impossible for most classroom teachers to devise appropriate questions.

Matching tests

Matching tests are restricted to lower-level learning, such as knowledge of terminology, facts, conventions, and principles. Although they are not easy to construct, they can include much specific information. Unless the teacher seeks the miscellany which is the strength of matching items, matching tests may be disregarded, because they add nothing to the proven virtues of fill-in and multiple-choice testing.

Standardized objective tests

A number of commercially published standardized tests are now on the market. These tests have been given to thousands of children at several grade levels, and from this mass testing age-group norms are available for comparison with national norms. The better tests supply test reliability, standard error of measurement, some information on the standardizing group, and a test manual for diagnostic purposes. They have been carefully constructed, and items which appear to be valueless have been eliminated, along with typographical errors and diffuse syntax.

These tests suffer, however, from the assumption that all children have been exposed to the same science learning, an assumption which ignores individual differences. Low scores on a standardized test do not necessarily mean little science learning; they may only mean that a child has not been exposed to *this* kind of science or that the child is not an experienced test taker.

There is a good reason to question the value of standardized tests. They are of questionable value in assessing the outcomes of science-teaching methodologies which are not committed to recalling facts and principles—which are, in other words, concerned with the observational, interpretative, and analytical aspects of science learning. There are no grounds at all for believing that standardized tests yield information commensurate with the cost and the time required.

Of the more than half a dozen nationally circulated tests that include either a separate science test or a science section, few have been designed for modern elementary-science instruction. The most susprising aspect of current evaluation is the relative inactivity of the new elementary-science curriculum projects in developing formal testing materials. Only the well-financed and well-staffed organizations such as the American Association for the Advancement of Science, the Science Curriculum Improvement Study, and the Elementary Science Study have the resources to develop and to test their materials on the touchstone of their objectives and curricula. By contrast, the secondary school science groups, which created revolutionary new biology, chemistry, and physics programs, began immediately to design new tests because the available tests were incompatible with their philosophy and procedures.

The Sequential Tests of Educational Progress

The STEP (Sequential Tests of Educational Progress) tests are written on four levels. Level 1 is for college freshmen and sophomores, level 2 for senior high school students, level 3 for junior high school students, and level 4 for children in the fourth, fifth, and sixth grades. Each test is available in alternate A and B versions. Each is made up of two sections containing thirty items each, timed at thirty-five minutes each, which is said to allow enough time for all but the slowest children. The content is distributed as follows:[17]

Biology	40%
Chemistry	16%
Physics	23%
Astronomy	8%
Geology	7%
Meteorology	5%

The tests are designed "to measure ability to use scientific knowledge to solve problems." Because this objective calls for reasoning ability as well as knowledge of scientific principles and information, the Educational Testing Service, which created the STEP tests, divided scientific reasoning ability into six sub-abilities:

1. To identify and define science problems	10% of all items
2. To suggest or screen hypotheses	25% " " "
3. To select valid procedures	17% " " "
4. To interpret data and draw conclusions	23% " " "
5. To evaluate critically claims or statements made by others	12% " " "
6. To reason quantitatively and symbolically	13% " " "

These percentages are not characteristic of the STEP elementary school tests, which concentrate on sub-ability 2, "to suggest or screen hypotheses," and which include a much lower percentage of questions designed to test ability "to identify and define science problems" and "to reason quantitatively and symbolically."

Content for the tests was selected from a list of "important," arbitrarily chosen "concepts and principles." Each question combines a concept or principle with one of the sub-abilities, so that each item tests the child's ability to apply one of the reasoning skills to the scientific principle. The questions are grouped into sub-sets, which follow brief descriptions of home-related situations explainable by a certain principle. These sub-sets are made up of three to ten questions:[18]

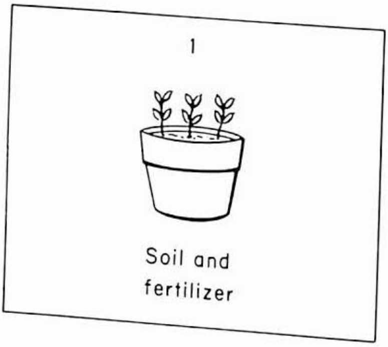
> This plan was used in order to make questions seem of more practical significance, and perhaps interest, to students and to make possible the development of questions which cut across the conventional dividing lines between the sciences, emphasizing the point that some of the same abilities are involved in the pursuit of all sciences.

One alternative of the four supplied for each question is correct, and there is some choice as to the test level which is to be used. For example, it is possible to use the level 3 test, which is designed for the seventh, eighth, and ninth grades, in above-average sixth grades. Unfortunately, there is no lower level of STEP tests than the two forms of level 4.

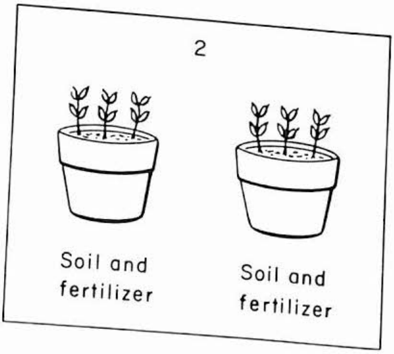
The STEP tests provide a detailed manual to help the teacher interpret results. For example, percentile bands (in contrast to percentile ranks), norms, lists of schools from which the norms were constructed, and validity and reliability estimates are supplied. In addition, there are helpful suggestions for analyzing performance on each test item, including an assessment of the child's grasp of the reasoning skills. The test, therefore has both feedback and diagnostic value. The value of this or any other test is dependent on the quality of the questions, however, and despite the generally high level of the STEP tests, some of the items are questionable. Consider, for example, questions 17–24 in the level 4B test.[19]

The Brown family wanted to plant a spring flower and vegetable garden. Mr. Brown said the first flowers to grow and bloom would be the crocuses, jonquils, and tulips.

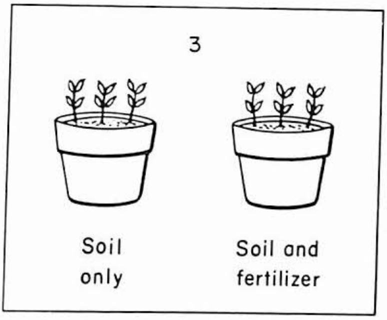
17. Their crocuses and tulips will bloom before their zinnias and marigolds partly because the crocuses and tulips
    (a) are watered more often
    (b) get more sunlight
    (c) are planted deeper in the earth
    (d) grow from food stored in bulbs
18. Sue Brown found some dandelions growing in the garden. The dandelion seeds were most likely
    (e) washed in by the rain
    (f) carried by the wind
    (g) dropped by a bird
    (h) planted with seeds from a seed package
19. Sue wanted to test some of her father's fertilizer to see if it would really make plants grow better. She thought of three different experiments.



Experiment 1. Add fertilizer to one flowerpot of soil. Plant three bean seeds. Watch them grow while giving them each the same care.



Experiment 2. Get two flowerpots. Add fertilizer to the soil of both pots. Plant three bean seeds in each pot. Watch them grow while giving them each the same care.



Experiment 3. Get two flowerpots. Add fertilizer to one flowerpot. Plant three bean seeds in each. Watch them grow while giving them the same care.

Which experiment would show if this fertilizer was good for the plants?

(a) Experiment 1
(b) Experiment 2
(c) Experiment 3
(d) None of the experiments above will tell her anything about the fertilizer.

20. Sue read on the back of the package of lettuce seeds, "Thin the plants to stand 4 to 6 inches apart in the row." What is the best reason for doing this?

(e) To give each plant enough room, air, sunlight, and water
(f) To get more plants into a garden
(g) To make the garden pretty
(h) To grow many kinds of plants

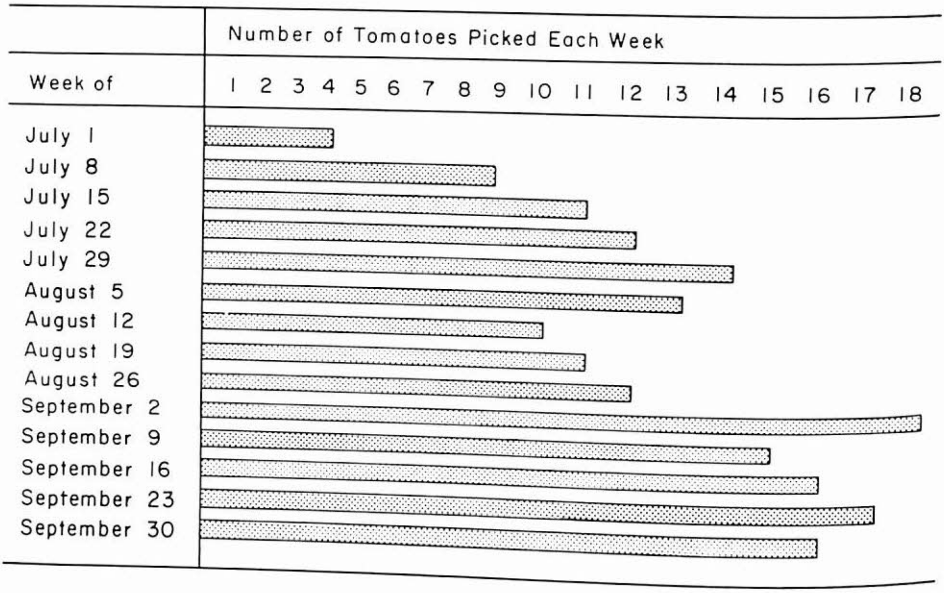
21. In the fall of the year, John still had many large tomatoes on his plants. He read the weather forecast in his newspaper.

Weather Forecast

Clear and colder tonight and tomorrow. Low of 28 degrees expected tonight.

Why should John gather in all his tomatoes?
(a) Frost was expected that night.
(b) There would be no more warm summer days.
(c) The tomatoes were all as large as they could grow.
(d) Plants need cloudy nights when the temperature is low.

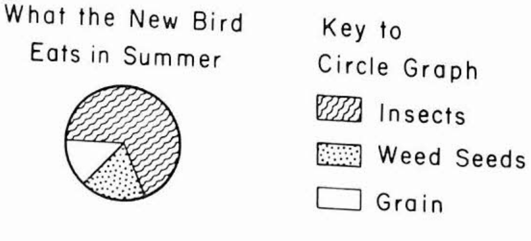
22. John counted the tomatoes picked from his garden each week. He kept this record:



During which week did John pick the most tomatoes?
(e) July 22
(f) August 5
(g) September 2
(h) September 23

23. A pair of robins built a nest in a tree near the window of Sue's bedroom. She watched them every day. Sue saw the eggs one day when the birds were away, but most of the time a robin sat in the nest. One day broken eggs were found on the ground, and the empty nest was not used again by the mother and father robin. Sue knows that the eggs were broken by
(a) the mother robin
(b) a strong rainstorm
(c) the father robin
(d) an enemy of the robins

24. Sue saw a new bird come to their garden. In a book she found its picture and a circle graph to show what the bird eats in summer.



From this graph, she was able to tell that this bird was
(e) helpful and ate mostly insects
(f) helpful and ate grain
(g) helpful and ate mostly weed seeds
(h) harmful and ate mostly grain

Response D, the suggested answer for question 17, is identified as a test of ability to suggest hypotheses. Choice of D may indicate ability to hypothesize, but the question is just as likely to be correctly answered from memory. Alternatives A and B may be excluded by children who know that the amount of water and sunlight falling on plants which are planted under the same conditions will be the same. They may also know that sunlight is ineffective in "germinating" seeds and bulbs. Therefore, it is not clear that Response D really tests how well children can propose hypotheses. However, the cumulative effect of the thirty-five items which presumably test hypothesizing may allow for some valid conclusions to be drawn.

Question 18 is also subject to prior school or home knowledge. On the other hand, question 19, which requires selection of a feasible procedure, is less likely to be responsive to memory. Question 20 does reveal the child's awareness of controlled experimentation as a source of data. It is interesting that questions 17 and 18 were correctly answered by only a quarter of the fourth grade normative group, and only one-third selected the "correct" answer for question 19. Only about a third of the group correctly answered question 23, which was designed to test ability to draw conclusions. The "correct" choice, D, is illogical in view of the given data. Items A and C may be rejected on grounds of "parental instinct"; B is rejected because Sue did not see the rainstorm, a fact which is not specifically stated. Item D is therefore the "best" answer, but it is not logically best. In order to answer correctly, the child must believe that the father and mother robin would not destroy the eggs which they had tended, and that the eggs could have been broken only by an "enemy."

This analysis shows how difficult it is to make up a paper-and-pencil test which successfully evaluates complex cognitive behaviors; there is no intent to diminish the obvious values of these tests. Indeed, if the conditions and qualifications of each question were spelled out in detail, and if the choices were more precise, the questions would be too difficult for children to read. Because of the way in which each question is written, however, it is impossible to tell if the child fails to select the proper hypothesis because he does not know what to look for. Perhaps he can neither examine the hypotheses objectively nor evaluate the plausibility of the hypotheses and relate them to scientific principles. Or he may rely on faulty memory for facts or principles. In this deeper sense, the test fails as a diagnostic instrument.

Even if this test does supply some information on the child's capacity to recognize appropriate assumptions, it gives no hint of his power to formulate hypotheses, to define problems, to select procedures, to draw conclusions, to evaluate critically, and to reason quantitatively in a practical situation. To the extent that "knowing about" is transferrable to "knowing how," these STEP tests are valid; unfortunately, the degree to which these two aspects of knowledge and behavior are correlated is one of the imponderables that confront science educators.

The Nelson-Mason Test of Science Comprehension

The Nelson-Mason test is another attempt to devise a test which is not limited to knowledge of facts and principles. This test is not comparable with the STEP tests, because it was devised for teaching critical thinking skills in a framework of selected content. This test has been selected for analysis because it was constructed by highly skilled professionals for a particular teaching context.

Its organization is similar to that of the STEP test; a series of situations to be interpreted, science principles to be applied, hypotheses to be tested, and conclusions to be drawn.[20]

> In working through the test items to the situations, the pupils become involved in making distinctions between what is given and what must yet be learned by making further observations, between facts and assumptions, between problems and hypotheses, and between inductive generalizations...and deductions from such assumptions or generalizations.

The test, composed of sixty items, was "standardized" for children in the fourth, fifth, and sixth grades. Fourth graders answer "correctly" approximately twenty-four items, fifth graders twenty-nine items, and sixth graders thirty-four items. A high ceiling has deliberately been incorporated, because a test which is not challenging deprives the best students of the opportunity to show how capable they are. The test was judged to be difficult for most fourth- and fifth-graders, although the questions were apparently not too difficult for most children to read with meaning.

Three of the eight test situations are biological, three are physical, and two are drawn from the earth sciences. The test authors did not itemize the individual thinking skills which each question attempts to elicit, although it is clear that each of the six STEP categories is included.

One of these "situations" will now be analyzed in depth, in order to show how content and interpretation are interrelated. The example chosen is based on the principle that most substances expand when heated. Ten objective questions were written to test the child's ability to recognize observations, assumptions, and deductions arising from the principle.[21]

> Numbers 36 through 45 refer to the following situation:
>
> > One hot July morning the center span of a low steel bridge across a river was swung open to allow a long string of barges to pass through. While the bridge was open the temperature rose many degrees. When the bridge tender tried to close the bridge again, the center span would not fit. It was too long!
>
> *Problems:*
>
> 1. What had happened to the bridge to prevent it from closing?
> 2. What could be done to get the bridge closed?
>
> Numbers 36 through 45 are statements that have some bearing on the solution of these two problems. Classify each one into one of these three groups:
>
> 1. Something that could be seen (observation)
> 2. Something taken for granted that has to do with scientific theory (assumption)
> 3. Something that can be figured out from scientific theory (deduction)
>
> 36. The center span of the bridge had increased in length. (1)
> 37. The center span was composed of rapidly moving molecules. (2)
> 38. An increase in temperature causes an increase in speed of movement of molecules. (2)
> 39. When the molecules of which a steel structure is composed move faster, the steel structure becomes slightly larger. (2)
> 40. If the steel bridge span was made of moving molecules, then increased speed of movement due to increased temperature caused the bridge span to become longer. (3)
> 41. Molecules move faster when the temperature goes up; molecules will slow down when the temperature goes down. (2)
> 42. If a hot piece of steel is cooled, its molecules should slow down, and the piece of steel should shrink in size. (3)
> 43. After the fire department had squirted cold water on the bridge span for about 15 minutes, the bridge swung shut without any difficulty. (1)
> 44. Cooling the bridge span caused it to become shorter. (1)
> 45. Cooling the bridge span caused the molecules in it to move more slowly. (2)

In order to answer correctly, children must know the meaning of such terms as "swing bridge," "center span," and "bridge tender." Items 36, 43, and 44 are described as statements. They are not logically equivalent: item 36 is described as a part of the situation, whereas number 43 is an additional fact. Item 44 is not an observation in the same sense, because it is a cause-and-effect inference, and a case can be made for defining it as an assumption. The fact that the bridge became shorter after cooling is not proof that these two events are causally related. This judgment is justified only if other variables have no effect, and if the bridge shortens only when it is cooled. Item 44 is meaningful only if children know or assume that metals decrease in length when cooled, other conditions remaining constant.

The child is supposed to classify items 37, 38, 39, 41, and 45 as assumptions. They are *all* either fundamental postulates of kinetic-molecular theory or applications of these postulates to this particular bridge. Items 40 and 42 are listed as deductions—that is, as predictions derived from kinetic-molecular theory. Items 37, 39, and 45 may with equal justice be included as deductions, because they are predictions applied to a specific problem.

The difficulty of labeling statements uniquely and precisely is no reflection on the Nelson-Mason test, which is a praiseworthy attempt to evaluate elusive and imprecise behavior. This test does reflect the degree to which arbitrary judgments must be made in test construction. A convincing case can undoubtedly be made for the particular categories chosen by the test constructors. The value of limiting the number of alternatives to three for this particular question is debatable, because the probability of guessing correctly is increased, but there are undoubtedly good reasons for this limitation. Some other questions supply two or, in some cases, four alternatives; most provide three. Obviously this test has feedback and diagnostic value, although the limitation to three choices precludes fine discriminations. Discussion of test answers with children will provide feedback.

The Concept Prerequisite and Development Test

This paper-and-pencil test was devised by Dr. H. Jess Brown, at Utah State University, for kindergarten through third-grade children. It is not a test of scientific process skills, but rather an instrument for diagnosing the readiness of children to profit from concept-centered instruction. The author chose four "abilities" which he believes are essential to the formation of concepts. He formulated ten questions to assess each of these abilities and included ten additional questions on concept application. The test is composed of these five sub-tests:[22]

1. Detection of Differences
2. Detection of Similarities

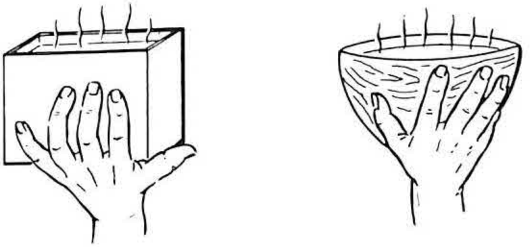
3. Logical Memory
4. Attention [to tasks]
5. Concept Formation

The questions in the first four categories are similar to those in many intelligence and reading tests. Children select an item in a set of drawings which differs from or which is like a key drawing; in the "Logical Memory" sub-test, they must recall oral directions; in the "Attention" sub-test, they must also rely on memory in order to answer correctly. The questions are open to the criticism that the "Attention" and "Logical Memory" tasks are quite similar, and that it is not possible to estimate on theoretical grounds the degree to which the tasks are valid measures of the child's capacities.

The ten questions on concept formation differ sharply, because six of them are based on scientific principles such as heat conduction, gravitational force, and musical pitch. The teacher is directed to explain briefly the particular principle, with appropriate demonstrations, before the children answer the question. The extract below is typical of the technique:[23]

> *Question #44:* Teacher: "Here is a drawing of another experiment. (Copper is a good conductor and wood is a poor conductor. So let's take a round wooden bowl and a square copper pan of the same thickness and put hot water in them, the same amount and temperature in each container, and hold one in each hand.) Draw a big X through the hand which would be the warmest."

44



> *Question #45:* Teacher: "Now I'll talk about gravity. The laws of gravity indicate that every object has a gravitational attraction for every other object. The strength of this attraction depends upon two things, (1) the size or mass of the objects or things and (2) the distance between them or how far apart they are. The heavier the objects are, the more attraction they have for each other and the nearer they are to each other the more they attract each other. When two things are large like the earth or the moon this attraction is very great, but when two things are small like you and I, the attraction between us is so small it is difficult to measure. When one thing is very big like the earth and one is very small like you or a ball the attraction is still quite large if the objects are close to each other.
>
> The earth attracts me quite strongly. I can jump up away from the

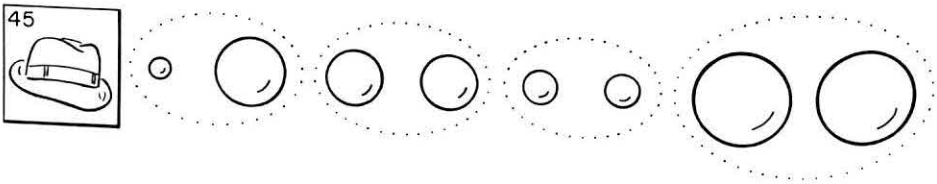
earth a foot or two [demonstrate] but the earth quickly and forcefully pulls me back down against it. You can throw a ball into the air away from the earth but it is quickly pulled back against the earth. Now I hope you have the idea that every object has a gravitational attraction for every other object, the large heavy objects attract strongly, the small light objects attract very weakly. I am attracted to you and you to me but the attraction is so very small we can only measure it with difficulty, but it is still *there* whether we feel it or measure it or not.

The other aspect of gravity, the distance factor, is interesting too. An object such as a ball is very much attracted to the earth when the earth is close to it. But if you put the ball out into space, away from the earth a great distance, the attraction of the earth for the ball and the ball for the earth may not be strong enough to ever bring the earth and the ball together again.

So you see gravitational attraction is greatest when objects are *heavy* and when they are *close together.*

Now we'll have some questions to see how well you understand the gravitational attraction idea.

Below, beside the picture of a hat, are some sets of balls which are much the same except the larger ones are *heavier* than the smaller ones. Their centers are all the same distance apart. Which pair of balls attracts each other with the greatest gravitational force? Draw an X between the two which attract each other the most, then turn to the next page."



The ideas presented will certainly be difficult for children who have not had earlier experience with them. Presumably, children who are better at remembering, attending, *and* forming concepts will be more likely to answer correctly, but the evidence that this is the case is not strong. Indeed, the test may merely reflect the ability of children to learn a new vocabulary without comprehending the scientific principles. In addition, certain methodological flaws may be present. For example, the value of the drawing in question 44 is questionable. This heat transfer demonstration is only valid if the two containers have the same shape, although for all practical purposes the wooden bowl will be cooler than the copper pan. Children encounter difficulties enough in picking out and controlling variables without confusing them by a partly uncontrolled demonstration. However, this drawing could be used to assess the child's ability to judge how well the experiment has been controlled. Furthermore, the subject matter of the first four sub-tests is not scientific, and therefore the test may be less relevant to scientific concepts and to the general capacity to learn scientific principles than if its content included tasks more closely related to the sciences.

Because the pertinent data are not yet available, it is not possible to judge the effectiveness of this test for children who have experience in Inquiry. Norms are given for approximately twelve hundred first-grade children in several western states. In addition to a calculated reliability of 0.78, "content validity was established through careful examination of the goals of nine recognized elementary curriculum projects and authorities."[24] The author states that it was his intention to harmonize this test with the "major curriculum developments in elementary science" in which these goals are recognized.[25] The stated correlation between the first four sub-tests with sub-test 5, "Concept Formation," is 0.34. This correlation, although indicative of some relationship, is not highly predictive.

Nevertheless, this test is a praiseworthy attempt to assess cognitive skills, and it should be valuable to the elementary school teacher who seeks deeper insights into the intellectual capacities of her children.

Competency Measures for "Science – A Process Approach"

The Commission on Science Education of the American Association for the Advancement of Science has prepared "Competency Measures" for classes which use *Science – A Process Approach*. (See Chapter 6 for an analysis of this curriculum.) Because the objectives in each exercise of this curriculum are stated as "descriptions of observable behaviors," the competency measures have been written to assess the child's mastery of these behaviors.[26] The intent is not to measure knowledge of the subject matter or how efficiently laboratory materials are used, but rather to find out if behavior has actually been altered in desirable ways. For example, to accompany the appropriate exercise in Volume 1A of *Science – A Process Approach*, there is a competency measure of the uses of classification. The child is asked to arrange a ball, a block, a slice of bread, a grape, an orange, a ladle, and an empty tin can in these three ways:[27]

1. Separate those which are inedible from those which are not inedible.
2. Separate those which hold water from those which cannot hold water.
3. Separate by experiment those which roll down an inclined plane from those which do not roll.

To accompany an exercise in observing seed germination in volume 2B, there is the statement that "a farmer has planted a field of corn."[28] The child is asked whether the farmer would see corn if he looked at his field later that day. He then modifies a drawing of a "corn seed" to show what it will look like just before it comes through the soil. Finally, he explains how to measure the rate of growth of a corn plant.

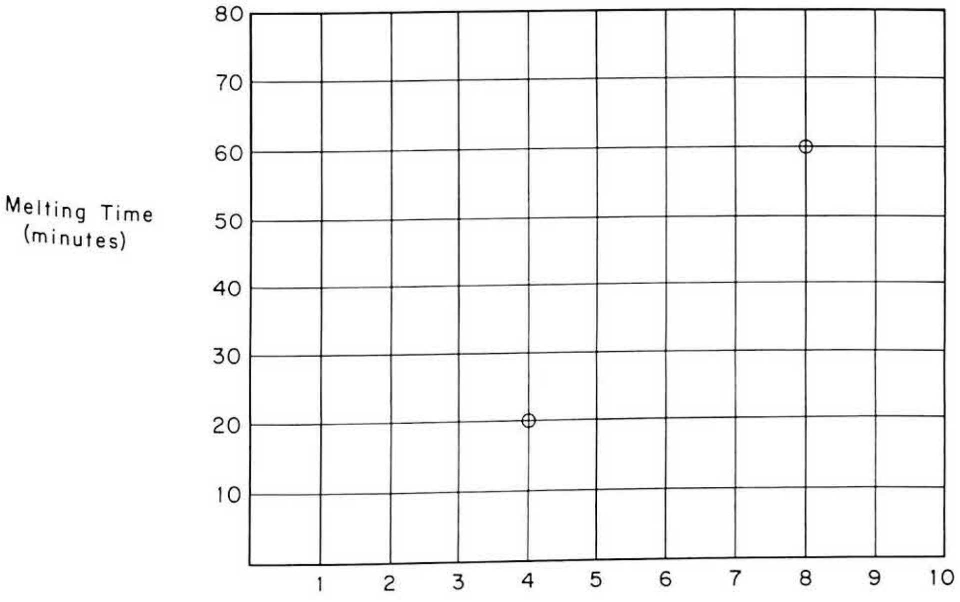
These competency measures become progressively more technical in their content and in the analytical skills which are necessary. For example, in the "Case of the Suffocating Candle" in Volume 4A, the child must make certain predictions:[29]

> 1.–2. Tell the child: I AM GOING TO DESCRIBE A SIMPLE EXPERIMENT TO YOU. TWO JARS OF THE SAME SIZE AND SHAPE WERE HALF-FILLED WITH WATER. FOUR ICE CUBES WERE ADDED TO ONE JAR OF WATER AND EIGHT ICE CUBES WERE ADDED TO THE OTHER JAR. IT WAS THEN OBSERVED THAT IT TOOK 20 MINUTES FOR THE FOUR ICE CUBES TO MELT AND IT TOOK 60 MINUTES FOR THE EIGHT ICE CUBES TO MELT. Present the child with a separate sheet of paper, or the chalkboard may be used, on which you have placed the following table of data:
>
> | Number of ice cubes | Melting time (minutes) |
> |---|---|
> | 4 | 20 |
> | 8 | 60 |
>
> Now ask the child to:
>
> > PREDICT HOW LONG IT WILL TAKE SIX ICE CUBES TO MELT. One check should be given in the acceptable column for task one if the child says some time between 30 and 50 minutes.
> >
> > PREDICT HOW LONG IT WILL TAKE TWO ICE CUBES TO MELT. One check should be given in the acceptable column for task two if the child says either 10 minutes or 15 minutes.
>
> 3.–5. Present the child with the following graph which has located on it the two points (use a colored pencil, if necessary, to make the location of the points clear) corresponding to the two sets of numbers in the table. Give the child a ruler and a pencil and tell him: YOU MAY MAKE MARKS ON THE GRAPH IF YOU WISH.
>
> > Ask: MAKE AN X ON THE GRAPH TO SHOW HOW LONG YOU PREDICT IT WILL TAKE FIVE ICE CUBES TO MELT. One check should be given in the acceptable column for task three if the child marks a time between 20 and 60.
> >
> > Ask: DID THE PREDICTION YOU JUST MADE INVOLVE EXTRAPOLATION OR INTERPOLATION? One check should be given in the acceptable column for task four if the child says he made an interpolation.
> >
> > Ask: MAKE AN X ON THE GRAPH TO SHOW HOW LONG YOU PREDICT IT WILL TAKE THREE ICE CUBES TO MELT. One

check should be given in the acceptable column for task five if the child says some time less than twenty minutes.

6. Now say: AN EXPERIMENT WAS CARRIED OUT IN WHICH TWO ICE CUBES WERE ADDED TO A JAR LIKE THOSE USED BEFORE AND WHICH WAS HALF-FULL OF WATER. THE MELTING TIME WAS FOUND TO BE TEN MINUTES. Add these results to the table of data before the child and ask him: PLACE A DOT ON THE GRAPH TO SHOW THIS ADDED INFORMATION. One check should be given in the acceptable column for task six if the child correctly locates the point representing two ice cubes and ten minutes.

7. Ask the child: WOULD YOU LIKE TO CHANGE EITHER OF YOUR PREDICTIONS INDICATED BY AN X ON THE GRAPH? MAKE ANY CHANGES YOU WISH NOW. Give the child one check in the acceptable column for task seven if he now changes his prediction for the melting time of three ice cubes to a position representing a time of approximately fifteen minutes.



This exercise is much more challenging than conventional elementary-science tests. Note the number of skills which are required—attending, remembering, computing, extrapolating, graphing, evaluating experimental evidence, etc. The child who displays the desired behavior has obviously become quite skilled in process thinking. Such skills do not burst forth overnight. They emerge rather slowly over a period of years, and then only if they have been the center of attention in elementary science during this time.

These "Competency Measures" are a promising addition to the evaluative arsenal of the elementary school teacher for several reasons: they are scientifically accurate, they are founded on psychological and educational theory, and they allow for gradual growth of cognitive skills. Children learn science by guided experimentation and observation, and therefore these tests of experimentation and observation are an important pioneering effort in the evaluation of the goals of science education. Many of these exercises may be used in the classroom without necessarily adopting the AAAS curriculum, but they will be valuable only to the extent that children are properly prepared by some kind of Inquiry-based instruction. Naturally, they will fit best if they are an inseparable part of *Science—A Process Approach.*

One disadvantage must be mentioned. In order to obtain reliable results, the teacher should test children individually, because he can observe and record behavior much more carefully. Many of the exercises are so long that there is too little time in the average classroom for such individual evaluation. However, it should be possible to revise some of the answer sheets so that older children may test themselves, thus minimizing testing time while giving the children immediate feedback. This procedure is particularly advantageous when children can accept evaluation without feeling threatened by it.

These "Competency Measures" are not standardized tests; reliabilities, validities, and norms are unavailable. But this is an advantage, because teachers should not compare the performance of their classes with other classes. What *is* important is that the teacher now has at his command a powerful tool for learning how well his children have mastered the perceptual and cognitive skills which are at the core of modern science.

The unique test

The unique test can only be prepared by the classroom teacher himself. It should be clear from the discussion of standardized elementary-science tests that unless the teacher purposefully and authoritatively covers a broad range of science content, and takes time for inquiry and critical-thinking skills, his children are not likely to score high on them. But teacher-pupil interaction in planning and working through a program of science is so important that the teacher, despite technical deficiencies in his knowledge of science, is the only person who effectively knows what his children can and can't do. Therefore, the permissive classroom, in which content is not constricted by an external course of study, by textbooks, or by external examinations, *is* unique. Standardized tests give much information about the class, but it is *absolutely* unimportant that these children know more or less (as judged by the test) than three thousand other fourth graders scattered throughout twenty school systems in the nation. The usual standardized test is a one-way Procrustean bed: it is always longer than the unfortunate child, who is to be stretched to fit it.

Validity

Most objective examination items used in the schools are limited to knowledge of facts and principles, and therefore fall into the lower cognitive levels of learning. Most tests, despite their outward form, are jerry-built from isolated and unrelated snippets of recall. It is at least as easy to prepare worthless essay and short-answer questions as it is to prepare worthless multiple-choice questions. Surely teachers and testers are *not* interested only in recall. They indignantly deny this charge, yet, in practice, they seek recall as the major outcome. Is it not necessary for the teacher to ask himself, "What do I need to know about each child's ability to infer? To see relationships? To make use of the knowledge of science which he has?"

Above all, tests should be *valid.* This is indeed easy to say, yet it is painfully obvious that validity, according to the stated goals of elementary-science instruction, is lacking. Does the test give the teacher the information which he is seeking? Of course, if all he looks for is a *word-for-word* definition of electron or insect, or a list of all the ways in which living things resemble each other, validity *is* attainable.

Even if the test is constructed to give insight into the reasoning processes of children, the knowledge obtained may be spurious.[30]

> One may . . . describe a biological environment and ask for predictions regarding the effect of a certain intervention. Students who have never dealt with ecological data will succeed or fail according to their general ability to reason with complex events; those who have studied ecological biology will be more likely to succeed, reasoning from specific principles, and those who have lived in such an ecology or read about it may answer successfully on the basis of memory.

Only the classroom teacher, who has worked for months with his children, is in a *position* to know on what basis the children have succeeded, even though he may not actually know which of these alternatives fits each member of the class.

Grouping items into situational sequences, as in the STEP and Nelson-Mason tests, is often proposed as a feasible technique for overcoming overemphasis on recall. Evaluators are hopeful that the child's ability to follow a chain of reasoning, to interpret a problem, to recognize hypotheses, to assess data, to deduce a course of action or a proposal from principles, to select reasonable alternative courses of action, and to propose appropriate solutions will be more susceptible to such testing. The difficulty of designing these tests and the inordinate amount of time required to formulate items and to reject worthless, confusing, and invalid items is an ever present burden.

Because good tests are so difficult to write, we should not expect most classroom teachers to construct valid paper-and-pencil examinations of the higher cognitive abilities. However, we can expect teachers to strive constantly and consistently to observe children's behavior in the classroom. Their observations may be invalid, unreliable, and retrogressive, but they are still a more reasonable base for assessing the impact of teaching in elementary science than is conventional testing.

Reliability

Reliability is a magic word in the lexicon of the test-maker. Reliability is defined as the consistency of test results within the same population, or within a representative sample from that population, if the test were to be given again. Unlike validity, reliability is relatively easy to measure. A test which is unreliable is probably invalid, but the converse is not necessarily true. If the test does not measure what it is designed to measure, and if its lack of validity is not known, consistency is meaningless. If "ability to propose hypotheses," for example, is *defined* as success on a test purporting to test this ability, a completely arbitrary validity is introduced, comparable to the facetious definition of intelligence as that which is measured by an intelligence test. This kind of validity is unsatisfactory, because it is based on the arbitrary assumption that *acceptance* by the test-maker creates validity.

Sampling

Comprehensive tests should include a variety of situations, ideas, facts and principles. It is the height of folly to conclude that a child cannot select pertinent hypotheses because he fails to answer *one* examination question which presumably demands this skill. Critical thinking is much too complex and intuitive to be sampled by a few questions, no matter how carefully they are fashioned. Some teachers have devised tests which are purposely restricted to a very few kinds of intellectual behavior—sometimes only one. These tests are given frequently in order to sample growth or lack of growth in these behaviors.

Each test item should be designed to test a specific ability or item of information, so that diagnostic feedback is possible. In the course of time, enough single-function questions should be used so that a composite judgment based on several tests and dozens of test items can be obtained. Unfortunately, conventional tests, despite rigorous analysis, tend to be diagnostically weak. No comprehensive diagnostic test is available, but if one did exist, it would be too difficult for elementary school children. This is a strong argument for giving many short, specially constructed tests in place of one or two comprehensive tests.

Test-makers frequently resort to the technique of "item analysis" in order to improve their tests. Item analysis is time-consuming, but frequently rewarding. Testers assume that the best students and the worst students (selected in groups according to prior performance or by the test results themselves) will perform differently on each test item. The best students select the "correct" answers, those which the test-maker himself selects. The poorer students, on the other hand, select the "correct" answers least often. Testers assume that the function of a test is to separate students in order to mark them appropriately. Therefore, test items which are more often answered correctly by inferior students than by good students are considered worthless, and items correctly answered only by good students are said to have "high discriminating capacity." Some questions are answered correctly by very few students, others by all or by most. Both kinds are also thought to be worthless, although test-makers often include some very difficult questions in order to give the best students an opportunity to display their ability.

In a sense, item-analysis is illogical, because it depends on circular reasoning. In practice, it is a useful device for detecting some, although not all, of the inferior questions, when it is used by a teacher who is well acquainted with the strengths and weaknesses of his children. With such a teacher, however, the need for this kind of paper-and-pencil science testing may be questionable. Furthermore, the purpose of testing in the elementary school is not to compare groups of children, but rather to find out as much as possible about each child. For this reason, tests should be diagnostic, rather than comparative; for re-teaching, not for setting up a baseline by which to mark children.

Before-and-after testing

One of the strengths of standardized testing is the availability of alternate forms whose reliability has been carefully verified and which are statistically equivalent—that is, children who score at the fiftieth percentile on one form will be very close to the fiftieth percentile on the other form. If teachers accept the validity of each form for their classrooms, and if they accept a high mark on these tests as a measure of successful learning, they can assess learning progress by giving one form of the test at the beginning of the school year or learning experience and the second form at the end of the year or experience. If maturation, concomitant learning, and practice in taking this test are ignored, growth indicated by the second test is presumably the result of instruction. The outcome of such testing is frequently dismaying, even following so long a period as a full year of concentrated instruction. As Fletcher Watson once remarked, "We must wonder how it is that after a year of instruction, the gains are so meager. Certainly such results must be discouraging to teachers."[31]

Standardized tests are probably inadequate evaluative instruments for discriminating between what children have or have not actually learned and what they can or cannot do. A year of living often exerts a much greater effect on a science test score than a year of instruction. That is, fifth-grade children, even without additional science instruction, do better on a test than fourth-grade children. This is perhaps to be expected, but it is nonetheless startling.

These doubts about the validity of written tests are intended to induce a healthy attitude of skepticism toward the claims of science testers and tests. It may be that the creation of practicable elementary-science tests which are also good diagnostic instruments is an unattainable idealization. Real learning may arise by such fine increments that it slips through the coarse mesh of cognitive testing. After all, the vast body of research in methodology and curriculum shows that the comparative differences in learning, learning as measured by these evaluative instruments, are insignificant. They may be *statistically* significant, but they are educationally unimportant.

Final tests

Final examinations in elementary science are not often used, because they have little to offer. They *can*, of course, provide extrinsic motivation, because they affect final marks. They may also stimulate students to review the year's work, although this review, without genuine previous learning, may be nothing more than a quickly forgotten cram. These advantages are negated by the fact that final tests are not directive; they cannot be used by the teacher to guide the child. They are the *end* of learning, not the beginning, because there is no opportunity for feedback and for relearning. Final tests in science therefore do not meet the criteria for wise evaluation.

The program in evaluation

The disparity between the implied freedom of Inquiry instruction and the explicitly detailed structure of a program precludes conventionally written programs as the center of progressive elementary-science instruction. There is, however, an unsuspected evaluative dividend which may accrue in programmed instruction, because programs facilitate evaluation of pupil failures and success. The teacher can know what each child is doing; he can see that one child is moving very slowly or because of frequent errors is moving through the program's error-correction cycles. If programs which stress the various cognitive and affective abilities were available, they could supply even more valuable information. Conventional programs do improve assessment of the child's learning of facts and concepts, because of continual sampling. Individual marking and grading is facilitated. Dr. William D. Hedges, who has carried out the best-planned research studies of elementary school science programming, emphasizes this point:[32]

> Teachers become more keenly aware of individual differences. For example, they become sensitive to the fact that the fast student who is on unit seven but who typically gets about 75 percent of the material on tests correct is not necessarily a more able student than the lad who is on unit four, but who is making well over 90 percent on his tests. How to grade at report time is, of course, a local problem. Some teachers have worked this out by dividing students into four quartiles on the basis of the speed or rate they work through the materials and then within these quartiles grade students with the usual A, B system. The card goes home to the parent saying that Susy May is in the top group in terms of speed, but her comprehension is low and perhaps she should slow down.

Not only is the programmed text or unit in itself an evaluative device, because behavior of children and their mode of response to the written questions may be observed, but, in addition, periodic tests are given. As soon as a child finishes a section, he measures himself against a sub-test; on completion of the final sub-test, he takes the final test. It may well be that the most important outcome of programs is achieved by the programmed test, which children take when they think they are ready, and from which they receive immediate feedback. Elementary school teachers will soon encounter programs in their science teaching, and it is important for them to be aware of the promise of programs for evaluation.

Evaluation of the classroom science program

This chapter has presented a detailed rationale for evaluating children's learning in science and has described a number of evaluative techniques and devices. Obviously, the rate and the quality of children's progress are the desirable criteria of teaching success. The teacher will certainly think about the difficulties which his children encounter and the reasons for lack of growth. The value of this analysis will be increased by objectively assessing his own teaching. This task calls for introspective imagination and ruthless self-criticism. The teacher must regularly examine his goals and methods, the variety and quality of firsthand experiences which he provides, and the value of the vicarious tools of teaching which he uses. The checklist below suggests the kinds of evidence for which teachers should look in judging their own teaching.[33]

I. In my teaching is there opportunity or provision for children to:

	None	Some	Much
(a) Raise questions and problems of importance or interest to them?			
(b) Study these questions and problems?			
(c) Help plan "things to do" in studying science problems?			
(d) State clearly the problems on which they are working?			
(e) Make hypotheses to be tested?			
(f) Gather accurate data (information) in a variety of ways:			
Through reading on the subject?			
Through taking field trips?			
Through watching demonstrations?			
Through doing experiments?			
Through talking to resource persons?			
(g) Analyze the data (information) to see how it relates to the problem?			
(h) Think about the applications of their science learnings to everyday living?			
(i) Think about science relationships and processes instead of merely naming things and learning isolated facts?			
(j) Bring science materials of different kinds to school for observation and study?			
(k) Engage in individual science interests?			

II. In my teaching do I periodically and systematically check on the children's growth in:

	None	Some	Much
(a) Ability to locate and define problems right around them?			
(b) Acquiring information on the problem being studied?			

(c) Ability to observe more accurately? ______ ______ ______

(d) Ability to make reports on or record their observations? ______ ______ ______

(e) Ability to solve problems? ______ ______ ______

(f) Ability to think critically? ______ ______ ______

(g) Ability to explain natural phenomena? ______ ______ ______

(h) Ability to distinguish between facts and fancies? ______ ______ ______

(i) Suspending judgment until evidence is collected? ______ ______ ______

(j) Being open-minded, or willing to change belief? ______ ______ ______

(k) Cooperating with others? ______ ______ ______

These checklists and suggestions are helpful to the extent that the teacher honestly and searchingly analyzes his daily classroom procedures. They are easily picked apart and criticized as a superficial and simplistic approach to an exceedingly complicated web of cognitive, attitudinal, and methodological competence. Nevertheless, a useful self-evaluative instrument must be short, general, and suggestive; not only is there no time to fill in a longer, more detailed evaluative scheme, but such a meticulous scheme will inevitably be artificial and restrictive.

The case for self-evaluation is strengthened by evidence that many teachers who are aware of modern science teaching objectives do not know that they themselves have not attained these objectives.[34]

Many teachers have not mastered the skills and knowledge required for modern programs of elementary school science, and they are unable to recognize weakness or strength in cognitive and affective behavior in the sciences. The teacher should surely be aware of his own strengths and weaknesses, an awareness which emerges from taking and self-diagnosing one of the higher-level STEP tests. In the past, institutions which prepare schoolteachers have not often provided opportunities for teachers to develop these insights. Perhaps they are not important, but it is hard to see how teachers can be sensitive to the child's needs and to his progress if they have never critically analyzed their own intellectual competence.[35]

Summary

Evaluation is the assessment of child growth toward his and the teacher's objectives. Its intent is to discover what each child is like, not to expose peer differences. Evaluation is essential in order to make wise decisions about children and about what they learn. Less importantly, evaluation also serves an administrative function.

Modern programs of elementary science are process-centered. They focus on the higher cognitive and affective components of behavior, which are difficult to measure by conventional assessment. Evaluative instruments in elementary science are still too crude to make such fine discriminations as the child's failure to propose hypotheses because he cannot do "If... then" thinking or because he cannot give the sustained attention necessary for discovering that some aspect of the natural environment is out of phase. For this reason, teachers of elementary science must rely on continuous, informal observation of actual pupil behavior as it occurs in experimenting, discussing, planning, observing, hypothesizing, inferring, and concluding.

Classroom learning and behavior is divided into the cognitive, affective, and psychomotor domains. The cognitive domain embraces the intellectual skills and the process elements of knowledge. The affective domain includes the emotional and attitudinal components which so decisively spur or retard cognitive learning. The psychomotor domain is restricted to physical and manipulative skills, which, in elementary science, are of minimal importance.

Paper-and-pencil testing, which has conventionally been the major instrumentality for assessing student learning, is deficient in several important aspects. Teacher-made tests are difficult to construct so that they are valid and reliable for assessing intellectual skills and experimental ability. Some progress has been achieved in the primary grades with "picture" tests, although the level of thinking for which they can be structured is relatively primitive. For intermediate and upper grades, essay and restricted-answer tests are useful, if their limitations are borne in mind. Objective testing, although convenient, is likely to be overwhelmed by addiction to recall, although cognitive and affective behaviors may, with care, be sampled. Standardized science tests are carefully made, but cannot provide sufficient diagnostic help, because intellectual skills are not precisely defined.

Written tests are also open to criticism because many questions which are presumptive probes of reasoning abilities are also answerable by recall of facts. Some of the best tests in the field, such as the STEP and the Nelson-Mason tests, are tests which minimize factual knowledge by presenting a series of related problems which may be solved by applying a scientific principle and some intellectual skills. The fact that both of these carefully constructed tests have some faults emphasizes the difficulty of constructing tests which will elucidate knowledge which is more than facts.

Programmed instruction in science holds a considerable evaluative potential, because the progress of children can be followed continually, and because the tests which children take when they are ready provide quick self-diagnosis.

Teachers must also evaluate their own teaching and intellectual processes honestly and searchingly, so that they too can grow. Tools for the purpose are perhaps even cruder than those for pupil assessment, but no other kind of evaluation is more potent for improving elementary school instruction.

For further study

1. How can you explain the dichotomy between evaluation for educationally valid purposes and for determining grades?

2. What flaws do you find in the authors' arguments supporting informal evaluation—for example, the statement that statistical interpretation is unimportant in elementary-science teaching?

3. Does the ungraded school effectively eliminate the major problems of formal long-term evaluation?

4. To what extent are evaluations valid when based on the three domains of classroom learning and behavior (cognitive, affective, and psychomotor)? Is this classification of classroom learning and behavior a valid organization of pupil behavior?

5. For the affective and cognitive domains, prepare at least two evaluation instruments—one for a lower level, one for a higher level—which are written in behavioral terms.

6. Construct a checklist by which the teacher may informally evaluate the child's interests and aptitudes in science.

7. Arrange a discussion of a scientific problem in class and tape-record the session. Play the recording to the group and constructively analyze the outcomes, the interactions between leader and students, and the participation of each group member.

8. Observe a science lesson in an elementary school and record the interactions according to the Flanders Interaction Analysis. Flanders, Ned A., *Interaction Analysis in the Classroom: A Manual for Observers*, rev. ed. (Ann Arbor: University of Michigan, 1964). Mimeographed.

9. Analyze the validity of several questions on a standardized elementary-science test.

10. Devise picture-test questions for young children to test concepts of heat, light, sound, erosion, growing things, and satellites.

11. A standardized test is given prior to a year-long science course. At the end of the course, the same test is readministered. There are no significant differences between the two tests' scores. What conclusions can be drawn concerning the teaching and learning processes?

12. Evaluate the adequacy of an elementary-science program as a diagnostic self-teaching device for children.

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The purpose of this chapter is to give the reader practical experience with Inquiry problems in the laboratory. These experiments have been devised for the college student in a college elementary-science laboratory; they are not intended for elementary school children. Several representative problems and plans for their resolution are presented. The first two experiments in each section of this chapter are described in detail. They are followed by several shorter, somewhat structured, problems which the reader should complete as practical exercises. These are preparatory to a third group of problems, which are a series of suggestions for Inquiry to be explored in the laboratory.

The illustrations which accompany these ideas are not intended to prescribe experimental procedures. It is desirable to approach these problems by different routes, and if contradictory results are obtained, so much the better! The resolution of differences is a necessary part of intellectual searching.

The reader is expected to convert these ideas into problems and to propose hypotheses and experimental designs to solve them. Reference to the criteria for planning experiments, in Chapter 7, pp. 257–258, will help the reader to evaluate these "model" experiments and to devise his own experiments.

Intellectual analysis of scientific problems, by itself, is insufficient to give the insight and understanding necessary for the laboratory pursuit of Inquiry. Therefore, students preparing to teach science in the elementary school should take time to outline their plans in detail and to work out the experimental consequence of

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Laboratory experiments

these ideas, recording their successes and failures for subsequent analysis.

The rusty-nail problem

The following experiment shows a heuristic approach to a laboratory problem. Specific suggestions will help you understand how the "elements" of scientific thinking may be applied in delineating the problem, analyzing cause-and-effect relationships, providing controls, recognizing and evaluating assumptions, formulating and validating hypotheses, collecting and interpreting data, and explaining related phenomena.

The key idea of this problem is that *some materials are better conductors of electricity than others.* One way of introducing this scheme is by what may be called the "rusty-nail" experiment. (This experiment, in one form or other, has been tested in several intermediate- and upper-grade classes as well as with curriculum materials classes on the college level.) Let us assume that, in your class, a child has asked why the wires which he connects to dry cells are made of copper. "Will other kinds of wires work as well?" This question is a natural point of departure for an experimental investigation of conductivity. Because it is impossible to test all materials, this study must be limited to easily obtained materials, such as common nails. Of course, nails are not customarily used in electrical circuits, for reasons which become obvious as the activity continues. Different diameters and lengths of copper, aluminum, and iron wire are clearly more suitable choices, but testing them may require equipment not ordinarily available in the classroom. An inquiry into the conductivity of common nails will serve as both an exemplar of simple "research," and an introduction for children to some of the important concepts of electrical conductivity.

The question, "Do all nails conduct electricity equally well?" will do as an initial statement of the problem. It is clear and reasonably specific. Because of its simplicity, we may assume that experimentation will provide answers. By limiting the problem to the testing of *conduction* in nails, we decrease the number of variables and the manipulative difficulties which may be encountered. In addition, the question appears to be well within the intellectual grasp of intermediate-grade children, and it requires neither expensive apparatus nor impossible feats of manipulation.

It may be argued that the question is still too diffuse to guide children effectively. What is meant, for example, by "all nails"? What kinds of nails? How long? How thick? How can they be tested for conductivity? What source of electricity is to be used? These important questions will be discussed in the following paragraphs.

Once the question is accepted, the next step is to propose one or more tentative hypotheses, which will not only "answer" the question, but which permit an evaluation of this "answer" from the experimental data. These hypotheses, therefore, should be so framed that they may be accepted or rejected at some level of confidence with the information obtained in the experiment. In short, the hypothesis must be so stated that it can be empirically tested in the laboratory. This requirement, so easily announced, is not always easy to fulfill. In this case, the hypotheses are readily evaluated. One hypothesis is that all common nails may be assumed to conduct electricity equally well, regardless of kind, size, or condition. Other hypotheses—for example, that nails do not conduct electricity—are also conceivable. The hypothesis that nails do not conduct electricity is perhaps the first one to investigate, because it is easily tested and has directive power. If our representative sample of nails does not conduct electricity, the problem is immediately solved. This result is informative because it answers the question, and it is directive because it prevents the investigator from wasting time. It is also typical of many research projects which, although they yield negative results, are still valuable in that they tell us what does *not* work.

Let us assume that this negative hypothesis is incorrect, and that we must return to the first hypothesis. The obvious technique is to try to force an electric current through the nails, and then to measure the amount of current which passes through each. The experimental apparatus for testing both hypotheses will presumably be the same. The electrical source, the connections, and the system for measuring current strength are all important. These elements should introduce no new variables. They should be easy to manipulate, safe, reliable, and inexpensive. A circuit for the purpose is presented in Figure 1.

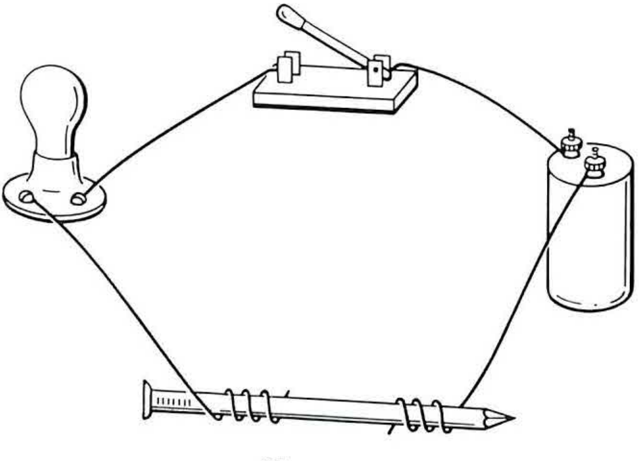

Figure 1

Source of current

The source of electricity must be powerful enough to pass a measurable current through each nail. A 110-volt alternating current (ordinary house current) is too dangerous for elementary school experimentation. Dry cells are an excellent substitute; a number six (1½ volt) dry cell is suitable. A quantity of these cells should be on hand to provide for increasing the current flow during the course of the experiment.

Electrical connections

The second experimental factor, the means by which the nail is connected to the cell, calls for two decisions. First, the gap between the dry cell and the nail must be bridged by a conductor; second, this conductor must be connected to the nail. Since the function of the conductor is to permit the flow of electricity to the nail, we can use insulated copper bell wire, because it is both inexpensive and a good conductor of electricity. The insulation will materially decrease the possibility of a short circuit in the apparatus. Actually, the choice of electrical conductor is not critical, providing that enough current for the purpose of the experiment flows through it, and that this flow does not change as a result of heating or of any other process within the conductor itself. Too narrow a wire, for example, may cause overheating, which reduces current flow and unnecessarily complicates the experiment. The selection of bell wire for the experiment is an example of the way in which previous knowledge may be applied to specific problems. The practicability of bell wire is easily tested by substituting a length of bell wire for the nail. This procedure will also give us a standard for comparing the conduction of the nails with the conduction of the copper bell wire.

Besides selecting the conductor, we must connect the wire (conductor) to the nail without damaging or otherwise altering the nail. This connection may easily be made with alligator clips; however, alligator clips have relatively sharp jaws in order to provide effective contact, and they may mar the surface of the nail. Therefore, we may simply wrap the wire tightly around the ends of the nail, even though the increased resistance will reduce the current flow. A length of friction tape wrapped around each connection will help to improve the contact. Here again, there is the implicit assumption that the method of experimentation does not significantly alter the conductivity of the nail. Throughout the course of this problem, there are a number of implicit or explicit assumptions. The experimenter should be aware of their existence, even though it may be impossible, within the framework of this experiment, to test their relevance. The validity of his results are, in large measure, directly dependent on recognition of these assumptions.

Measurement of current strength

Some device for measuring the strength of the current which passes through the nail is necessary, for current strength is an index of the ability of the nail to conduct electricity. The ammeter, which is usually used to measure current strength, gives accurate and reproducible results. But because the ammeter is expensive and easily damaged, it is not likely to be available in elementary schools. A practical, though less accurate, indicator of current flow may be made out of a flashlight bulb. The bulb will shine brightly if enough current flows through the circuit, and will not shine if the current flow is too low. On the assumption that brightness is directly related to current strength, the observer judges current strength by observing whether the bulb is very bright, bright, or barely glowing. If, for example, the bulb is brighter in test two than in test four, we interpret this to mean that the test-two nail passes more current than the test-four nail.

At this point, let us introduce several additional assumptions. We assume that if the current is strong enough the bulb will light. We assume that the dry cell does not change with use (e.g., does not become weaker) and that changes in bulb brightness are the result of actual differences in conductivity of the test nails. If the dry cell is not a constant quantity, experimental results will be misleading, because the measurements will reflect changes in the strength of the current source, as well as the kinds of nails. Another assumption is that the direction of current flow in the circuit is immaterial. This assumption may be tested by reversing the connections at the terminals of the dry cell.

In experimentation, we are especially interested in finding out what happens when the experimental factors are changed. In this experiment, the conductivity of different kinds of nails is examined. We will need an assortment of nails—shiny, dull, rusty, headless, thin, thick, short, and long. A systematic record of the different nails and their effect on bulb brightness is necessary to organize and interpret the data. Figure 2 is an example of a chart which has been used for this purpose.

Examination of these data uncovers possibly significant relationships. In this experiment, the condition of the surface of the nail appears to affect the amount of current which it carries. These data are incomplete in the sense that we have not attempted to compare nails which are "exactly" alike in every way but one, that one being the experimental variable. The question which this experiment is designed to answer does not require that sophisticated an analysis; therefore, this simpler method is suitable. The data chart is clear and instructive. An unambiguous presentation of data helps the experimenter to understand and interpret his results, and is therefore indispensible.

Are the results such that the original hypotheses must be rejected? The hypothesis that common nails do not conduct electricity must be discarded, of course, because it is contradicted by the data. The hypothesis that all kinds of common nails *do* conduct electricity equally well must also be discarded, because it is refuted by the evidence. The problem originally proposed has now been solved, but in a rather unsatisfactory way, because the obvious differences in conductivity are unexplained. Therefore, an alternative hypothesis based on these experimental observations must be proposed in order to account for these differences. Can it be that rusty nails are either poor conductors or non-conductors of electricity? The astute observer notes that the rusty five-inch nail shows some conductivity. Is this effect a result of its greater length, or of its coating of rust? How may these possibilities be tested? One test is to compare two rusty nails that are alike in every way but length. The possibility that the copper wire connected to the nail has worn away enough rust so that some flow of current takes place may be tested by changing the way in which the nail is connected into the circuit.

Other factors, such as the diameter of the nails and their chemical

Description of nail	Degree of Conductivity as Shown by Estimation of Relative Brightness: Very Bright	Medium Bright	Low Brightness	No Light
Shiny 2" nail	✓			
Shiny 3" nail	✓			
Shiny 5" nail	✓			
Rusty 2" nail				✓
Rusty 3" nail				✓
Rusty 5" nail			✓	
Shiny headless 2" nail	✓			
Rusty headless 2" nail				✓

Figure 2

composition (aluminum, soft steel, or iron) may also be tested in much the same way. Obviously, the experiment may be extended far beyond the bounds of the original inquiry.

One of the most important reasons for experimenting is that the test data are the raw materials from which conclusions and predictions are derived. Once predictions about electrical conductivity have been proposed, the experimenter is ready to begin another cycle of experimentation, in which predictions are transformed into hypotheses. For example, if aluminum nails were not tested in the original experiment, several predictions about their conductivity may be made. It may be that aluminum nails, whatever their length, do not carry electricity. However, it is more reasonable to suppose that aluminum nails are good conductors of electricity. Certainly, if length has been eliminated as a significant variable in the earlier experiment, it is likely that length is unimportant in the conductivity of aluminum nails. The experimenter may therefore think of an experiment to test this hypothesis. Eventually, a number of hypotheses will be proposed, tested, and either accepted or rejected. The majority will probably be rejected.

The hypotheses which are accepted are as valid as the experiments on which they are based. To the extent that the nails tested are representative and the experimental design has eliminated extraneous variables, answers to the questions which were originally proposed have some degree of validity. It would be most unwise, however, to overextend the generalizations which emerge from such limited experiments as the rusty-nail experiment.

A problem in heat loss

Theoretical explanations of heat phenomena are a striking example of a conceptual scheme. Modern theory is both powerful and elegant as a tool for interpreting the endless variety of events in which heat is a determining or complicating factor. It is possible, of course, to plunge boldly and unwisely into a study of heat theory. This, however, is certain to be a fruitless approach for children, and perhaps just as meaningless for adults who lack the direct experience with heat phenomena which experimentation provides. The problem in heat dissipation that is the focal point of this section may be analyzed in terms of molecular motions and the kinetic energy of molecules. This approach, however, is obviously impossible when these notions are as yet unformed.

One of the purposes of science instruction in the elementary school is to provide children with a sufficient diversity of experience so that the conceptual structures of science begin to make sense. The problem in heat loss which follows is an example of how experimentally derived facts lead to scientific principles. We have selected as a problem the capacity of different substances to conduct or retard heat flow. Let us assume that this question is proposed: "Are all materials equally able to conduct heat?"

Adopting the conductor-insulator terminology which is usually used in heat-transfer investigation, we may propose at least two hypotheses: (1) there is no significant difference in the insulating ability of various materials; (2) some insulators are significantly better than others. The knowledge which children and adults possess is undoubtedly sufficient to eliminate the first hypothesis, even though testing the second hypothesis will confirm or deny the validity of the first hypothesis. Therefore, to test the second hypothesis, it is necessary to select appropriate materials and to devise some reliable, controllable procedure for measuring the rate at which they conduct heat, under circumstances which permit direct comparisons.

Efficient insulators presumably transmit heat slowly, and therefore a substance at an elevated temperature will cool less rapidly if it is covered by a good insulator than if it is covered by a poor insulator. Accordingly, we must invent a procedure for measuring, directly or indirectly, the amount of heat retained during a fixed time period. It is also possible, although much more difficult, to measure directly the rate at which heat is transmitted within the insulator. This may be

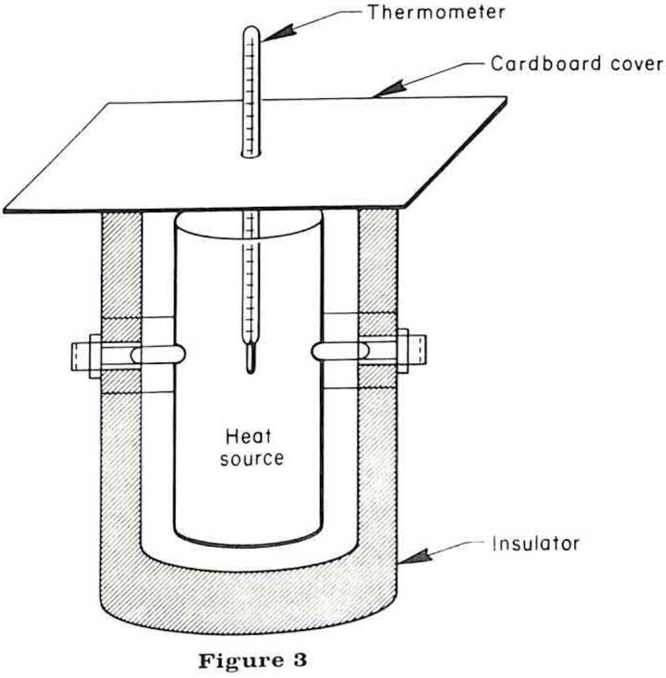

Figure 3

done by taking the temperature of the insulated material at regular intervals. Note that temperature is assumed to be a direct measure of heat content, an assumption which is valid only in certain cases.

In order to measure heat conductivity (the inverse of insulating ability) directly, we will apply heat to the insulator and measure the rate of heat flow. It is much more convenient to measure heat flow through the insulator indirectly. To do this, an instrument called the calorimeter is often used. The calorimeter holds a known weight of water, whose temperature change depends on the rate at which the water loses or gains heat.

Figure 3 illustrates this apparatus. The larger outer container is filled with the insulating material to be tested. The possibilities for testing are limitless—water, air, iron filings, ground cork, sand, styrofoam, fiberglass wool, and wood shavings are suggested. The degree to which the insulating material is divided may play some part in its ability to retard the flow of heat. Each pebble, for example, may be an excellent insulator, but if these pebbles fit so loosely that large air spaces are present, we may merely be testing the insulating ability of air. One precaution, therefore, is to fill the outer container as full of the test material as possible, excluding to the best of the experimenter's ability any other substance. Some of the test materials—styrofoam, for example—may contain a considerable amount of air, and their data are really a composite of the insulating capacity of air and the test object.

The small container, which is imbedded in the test insulator, is the high or low temperature source. The experiment may be run with a minimum of two pieces of apparatus, one of which is a control. Let us begin by pouring heated water into the inner container and covering it immediately with a cardboard, through which the thermometer is inserted. By comparing the rates of temperature decrease for each insulator, we will be able to judge their relative efficiencies in retaining heat. If the rate at which the temperature decreases is approximately the same for all the insulators, the first hypothesis is verified. If the rate of decrease is consistently different from material to material, the second hypothesis is probably correct.

Obviously, the experiment itself must be still further refined if this conclusion is to be justifiable. At the beginning of each trial, the inner container must hold the same quantity of heat. Presumably, equal volumes of water in the same containers (perhaps the shape of the inner vessel affects the rate of conduction) at the same initial temperature satisfies this condition. Water boils at approximately 212 degrees Fahrenheit. The boiling point is affected by atmospheric pressure, but if the experiment is carried out in a reasonably short time, pressure variation should be negligible. The temperature of boiling water is therefore constant, and with equal volumes of water the amount of heat is constant. A large container of boiling water stored close at hand is an excellent source of constant-temperature water.

Suppose, however, that we use a standard measuring cup to transfer this boiling water to the test container. If the cup is initially at room temperature, its temperature will rise as the water which it contains is cooled. The second trial, if the measuring cup is warm, begins with the heat source at a temperature higher than in the first trial. Should this occur, the data will be somewhat inaccurate.

One technique for minimizing this error is to begin the experiment with as many measuring cups as there are experimental setups. The temperature drop of the water should be relatively constant for each cup. It is also possible to substitute for the cup a long-handled ladle which is immersed in boiling water and is therefore at an initial temperature of 212 degrees Fahrenheit. If the ladle is returned to the boiling water for a few minutes after each filling of the calorimeter, the ladle will remain at the proper temperature. There are other ways to eliminate these heat transfer losses. No matter which method is used, the experimenter should try to maintain equal starting temperatures.

The temperature readings taken at equal time intervals are conveniently tabulated in chart form. Figure 4 is an example. The time intervals are five minutes; the temperatures for each insulator are written on the appropriate line.

Insulating Material	Temperature at 5-Minute Intervals									
Water	96	91	86	81	77	72	67	64	60	58
Air										
Cork	96	93	90	87	83	80	76	72	70	68
Sand										
Fiberglass wool										
Iron filings										
Wood shavings										

Figure 4

Should the first hypothesis be rejected? The insulators differ significantly in their ability to conduct heat, but the experimenter must decide whether or not these differences are sufficiently large to exclude chance or random errors. Assuming that all the variables except the insulation are kept reasonably constant, consistent differences, even though small, cause us to accept the second hypothesis.

This experiment is appropriate for several reasons. The materials are simple, inexpensive, and safe, and the experiment is fairly easy to control.

Two partially outlined investigations

The analysis of the two experiments which follow is incomplete so that you may plan and carry through each experiment, formulating your own hypotheses, assumptions, and conclusions.

Electromagnets

Explanations of magnetic phenomena are often difficult for children to understand. This is not surprising, because these explanations have slowly grown out of many years of struggle with the chaos of natural phenomena. The physical effects of magnetism, on the other hand, are easily observed. The first level of understanding comes from informal play with magnets. Children soon realize that the number of magnetic materials is small, and that these materials are identified by their interactive effects. With increasing conceptual maturity, they accept the existence of some kind of invisible force which fills the space between the magnet and the object which it attracts. Magnetic field interaction is a theoretical construct, defined by the physical evidence of motion and by the effort required to separate the magnet and the object. This magnetic force is so intriguing and scientifically important that it can

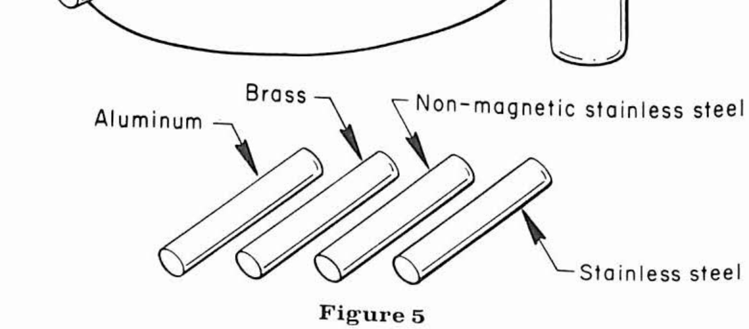

Figure 5

serve as a conceptual center for many experiments in elementary science.

The relationship of electrical current and its magnetic field adds to the educational potential of magnetism. The common doorbell is an example of a device in which an electromagnetic interaction occurs. The current flowing through a coil of wire generates a magnetic field; this field interacts with a metal "hammer," causing the bell to ring. The energy of electrons in motion is transformed into mechanical energy.

Several of these electromagnetic relationships are investigated in the experiment described below. Let us assume that the investigator knows that an electromagnet may be constructed out of a coil of wire wound around an iron core. Several questions about this simple apparatus quickly come to mind. Must the core be iron? Can other metals be substituted without affecting the strength of the magnet? The apparatus of Figure 5 will make it easier to study these possibilities.

The metal bars are alike in diameter and length. They differ only in composition. What effect will changing the bar have on the strength of an electromagnetic field? The reader can test his hypotheses by passing an electric current through the wire coiled around each bar.

Several assumptions are built into this experiment. For example, the current flow must be constant. In Figure 5, the source of current is a dry cell. Dry cells, however, run down after extended use. Despite this drawback, they are almost mandatory for elementary school experimentation, because they are safe and convenient. As in the rusty-nail experiment, a decrease in current flow from a weak dry cell leads to contradictory results. What are some of the other assumptions?

In order to gather enough "quantitative" data to test your hypotheses, some device for making quantitative measurements must be added. A technique for measuring the relative strength of each electromagnet is illustrated in Figure 6. This arrangement is simple and easily set up, yet is quite sensitive. Certain precautions should be taken in order to

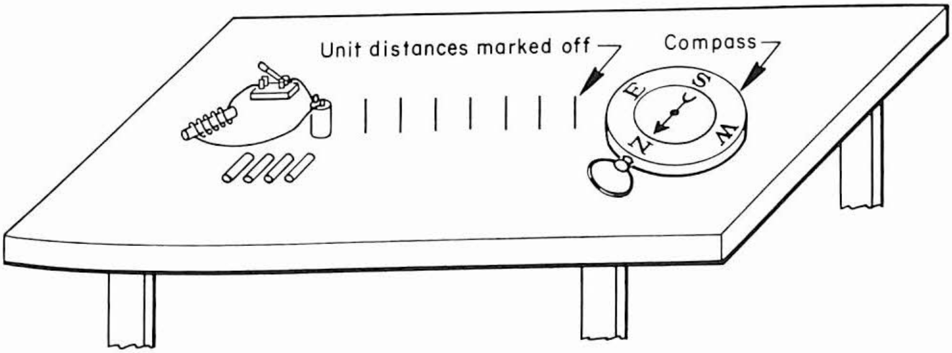

Figure 6

obtain reliable results. It should, for example, be used in exactly the same way for each trial. The orientation of the electromagnet should also be the same each time. The compass is moved slowly toward the electromagnet until the needle barely quivers when the current is turned on. We assume that the distance of the compass from the electromagnet when this happens is a measure of magnetic strength. If this assumption is justified, it follows that the greater the distance, the greater the strength of the electromagnet. You may invent other ways to measure magnetic strength, and it will be an instructive exercise in experimental ingenuity to try them.

Other variables governing the strength of electromagnets may be tested with this apparatus. For example, what will happen if the number of turns of wire around the core is increased? Will field strength change measurably if these coils are tightly wound? Loosely wound? If the wire is uninsulated? What will happen if the current flow is increased by connecting two or more dry cells in series? Does the diameter of the wire, the kind of wire, or the type of insulation change the strength of the electromagnet?

You should perform this experiment yourself as a practical exercise in investigation. In order for this experience to be of value, it is essential that you state the problem clearly, list the hypotheses and assumptions, organize the data, and show their relevance for accepting or rejecting your hypotheses. As a final step, the acceptable hypotheses should lead to the formulation of a prediction or explanation of related magnetic phenomena.

The intensity of light as a function of distance

Everyone knows that as he walks toward a distant source of light it seems to become brighter and brighter. Of course, no one attributes this increase in brightness to an increase in intensity of the source. The reasonable assumption to make is that the light itself does not change; that instead, the amount of light which strikes the eye increases, creating the impression of greater brightness. Why does brightness decrease with distance? Is the relationship between intrinsic brightness and observed brightness, if it exists, one which may be extracted from readily obtained data?

These questions imply that the discovery of a quantitative or a qualitative relationship is equivalent to explaining what happens. Stating a scientific law is not tantamount to giving a scientific explanation, because a law is a description of physical pattern, of a regularly occurring phenomenon. It is not a prediction which is drawn from a comprehensive theoretical structure. The relationship, when discovered, answers the question of *how* brightness varies with distance. This resolution of the problem is merely a first step in answering the question of why.

How can we find a relationship between intrinsic brightness, apparent brightness, and the distance between observer and light source? Is it possible to state this relationship in either quantitative or semi-quantitative terms? Suppose that the observer guesses that as his distance from the light is halved, the apparent intensity doubles, and that as the distance is doubled, the light intensity is halved. In this hypothetical case, if all other factors are constant, apparent light intensity is inversely proportional to distance from the source. The investigator will surely not guess that light intensity increases with distance, because this hypothesis is immediately contradicted by what he has seen. However, other ways of coupling apparent light intensity and distance are as plausible as the inverse proportion suggested above.

Which of these fits the evidence? How can we design an experiment to test each hypothesis? Whichever is chosen, acceptance or rejection must rest on the experimental data and on the researcher's estimate of the reliability of his data-gathering technique. The two techniques which are briefly described are merely suggestions. These are other, perhaps better, ways to investigate this problem.

Instruments for measuring light intensity, such as the photographic light meter, are easy to obtain. The light meter converts light energy into enough electrical energy to give a quantitative measurement of the light intensity falling on the meter. Therefore, as the distance from the light is systematically increased or decreased, the meter reading will change accordingly. If, for example, the apparent intensity decreases directly as the distance increases, the meter reading for each unit change in distance should be approximately equal, whether the change is from two to three feet or nine to ten feet from the light source; the reading at a distance of five feet should be twice as great as that observed at ten feet. Within the limitations of this rather crude experiment, the hypothesis is quickly tested. If it is invalid, the experimenter will then turn to the other hypotheses which he has formulated to see if they are acceptable.

A more interesting way of attacking this problem is with a Polaroid-Land camera, loaded with a special negative film available at camera stores. Photographs of the light source are taken at various unit distances without changing the lens opening. Everyday experience assures us that brightness of the photographic image decreases as the distance to the source increases. This technique suffers from the disadvantage that numbers, the raw materials from which exact relationships are inferred, are not generated, and therefore quantitative comparisons are difficult to make. By comparing image brightness of the negatives, the experimenter will be able to arrange them in order of intensity with some degree of reliability.

Either or both of these methods may be tried, according to the apparatus and availability of darkened rooms. The reader should design an experiment to discover for himself the quantitative relationship of light intensity and distance from the light source in which hypotheses, assumptions, data, inferences, experimental difficulties and errors are thoroughly analyzed. A comparison of the results of two methods is an instructive exercise in discovery.

Suggestions for investigation

Each of the three physical-science topics briefly described below leads to at least one fascinating scientific inquiry. With the information supplied, you should be able to formulate the problem, propose one or more hypotheses, and devise an experiment to test these hypotheses. You may find it necessary to turn to reference sources for additional information in order to plan your experiment as efficiently and as carefully as possible. Do not be disappointed if the results are confusing, or if the experiment fails to work as you expect. Failure is frequently encountered in scientific research, and it should encourage the investigator to rethink his design and his expected outcome. Only in the desiccated routine of verification experiments is success guaranteed.

Heat conductivity

Very young children soon learn not to touch hot metallic objects without taking precautions. In the home, the housewife usually handles a hot pot with a cloth potholder. She knows, however, that in a short time even the potholder becomes unbearably hot. Some potholders take a longer time to heat up than do others. The insulating efficiency of the different kinds of potholders may be experimentally compared. A number of assumptions and variables must be isolated, and it will be a challenging task to plan the necessary controls within the limits of convenient experimentation.

Finding the rate at which different kinds of pots radiate heat is a similar problem. Suppose that you are given the task of finding out whether copper, aluminum, or iron pots cool off most rapidly. How will you phrase the problem? What hypotheses will guide your experimentation? What assumptions must you recognize? What variables should you control? How will you record the data? When you come to some conclusion as to the relative efficiencies of the different kinds of heat conductors, verify your results from a table of heat conductivity in a standard physics textbook.

Air pressure

Physical phenomena which are dependent on atmospheric pressure are frequently misinterpreted. Consider, for example, the classical experiment in which a glass tumbler, filled with water, is covered with a card, and the entire system of tumbler, water, and card is inverted. (See Chapter 4, p. 135.) It is reasonable to expect that the water will pour out of the glass, to the consternation of the demonstrator. Reason, however, is not always a sound guide in experimental endeavors, and the water remains in the glass, held in by a more or less tightly adhering card. If the glass is half filled with water, and the experiment repeated, the same thing happens. Surely, in the latter case, the pressure exerted by the air trapped in the glass is equal to the pressure of air outside the glass. The total force pushing the card down must be equal to the sum of the air pressure inside the glass and the pressure exerted by the water, and this total is obviously greater than the external pressure of air which is presumably holding the card in place. What holds the card on?

An investigation of the forces which act makes an interesting, although somewhat damp, experiment. We suggest that you try odd-shaped glass containers, polyethylene and styrene jars, liquids other than water, and a variety of cover materials in your research. You may not come to a valid conclusion about the different forces which hold the card in place, but you will profit from this experience because of the opportunity to try out your skills in Inquiry.

Wetting agents

The rather surprising characteristics of liquid surfaces provide many opportunities for simple laboratory experimentation. Physics students are often astonished when their instructor "miraculously" manages to float a razor blade or a needle in a container of water. This, they are told, occurs because the surface tension of water is sufficiently high to float a dense metal object on a "skin" of water. Floating is not a proper description, because an object which floats displaces its own weight of water. In the case of the razor blade or the needle, close examination of the downward bulge in the water surface should dispel the notion that enough water has been displaced to cause the object to float.

If, indeed, a surface-tension "skin" is responsible, decreasing the surface tension should make it much more difficult to float the razor blade. Wetting agents, such as detergents, decrease surface tension forces in water. With this information, it is possible to think up an experiment in which the surface tension of water is systematically changed and, from the data, to draw reliable conclusions about the effect of wetting agents.

Kinetic energy

Objects of different mass, falling from the same initial height above the ground, strike the ground with the same velocity but different kinetic energies. It is difficult to measure the velocity of falling objects, because of experimental complications; it is relatively easy, however, to measure the kinetic energy of falling objects and to compare these measured kinetic energies with a prediction derived from physical theory.

The track in Figure 7 is a seven-foot piece of wooden cove molding, which may be purchased at any lumber yard. If the molding is thoroughly moistened and left to dry as illustrated, it will hold this shape for a number of days. By rolling marbles down the track, it is possible to obtain the necessary quantitative data by which the kinetic energy of each marble may be calculated. How can you use this apparatus to measure the kinetic energy of falling (rolling) balls?

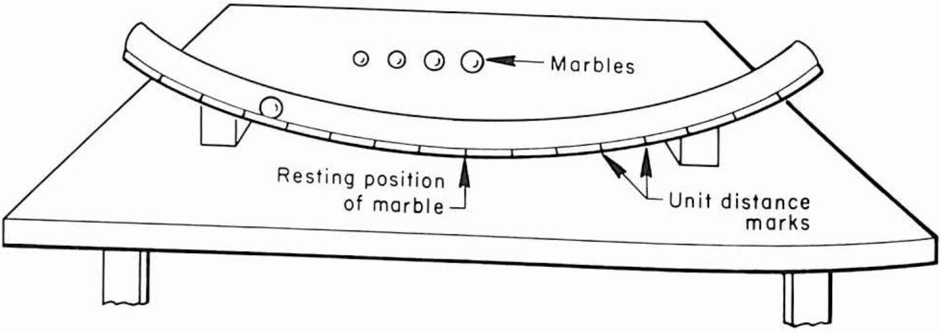

Figure 7

The biological sciences

Students are often misled by the ease with which they seem to learn concepts in the biological sciences. Their familiarity with individual organisms and with the biological systems of which these organisms are a part lulls them into the belief that biology is the least difficult of the sciences. The emphasis on biology which has characterized so many elementary-science curricula is, in part, a consequence of this apparent simplicity. This attitude of both children and adults is not in accord with the comprehensive theoretical structure of scientific biology.

The experimental activities in this section are organized into a rather loose conceptual framework, in which some biological relationships may be seen. None of the experiments suggested in this chapter is complete unless the data and conclusions are shown to be natural consequences of one or more of the themes and schemes of the sciences. If this framework is functional, the learner should be able to fit into it each bit of information and each biological idea.

The subject matter of the biological sciences has been divided, for the purposes of this chapter, into these general classes:

1. Animal behavior.
2. Animal structure.
3. Plant behavior.
4. Plant structure.
5. Inter-relationships.

Each class includes many of the schemes of science, some of which are listed in Chapter 5, pp. 179–181. The content of the Inquiry experiments in this section falls naturally into one or more of these schemes and classes.

The fifth class, "Inter-relationships," is important because it is through knowledge of biological inter-relationships that behavior and structure become meaningful. By inter-relationships, we mean the mutual effects of living organisms on their environment. Ecology is another name for this interaction of the physical and biological environment.

A plant is more than a numerical sum of its evolutionary identity, cell-tissue and vessel arrangement, growth behavior, mode of germination, and adaptations for survival. It is also an inhabitant of an environment in which the underlying rock strata, the soil, the weather, and the native plants and animals have shaped its life course. The individual disciplines which collectively we call biology must somehow be blended into a unity which is the "organism-habitat." Without the habitat, we cannot know the individual. Without the individual, the habitat is barren.

The student is urged to fit the information which he gathers from the investigations of this section into an ecological framework. This is not an easy task at best, because ecology is still a relatively uncharted domain. Perhaps the nearest approximation is to match the facts and concepts that are discovered with the relevant ecological schemes and the arbitrary framework of classes proposed above.

Animal respiration

We know from long exposure to the facts that, by breathing, animals obtain oxygen from the air which surrounds them. We know also that this oxygen is chemically combined by the respiratory machinery of animal cells, and eventually excreted in combination with carbon as carbon dioxide. The knowledge which most adults have of this respiratory process is understandably taken from textbooks or from other vicarious sources of information. The normal limits of school experimentation preclude the direct demonstration of the role of oxygen in metabolism.

The experiment which follows is an investigation of the rate at which animals use oxygen. The question may be broadly, perhaps too broadly, stated as "What is the respiratory rate of laboratory animals?" The suggested apparatus in Figure 8 is a simplified version of the original, which was invented by the physiologist Otto Warburg.

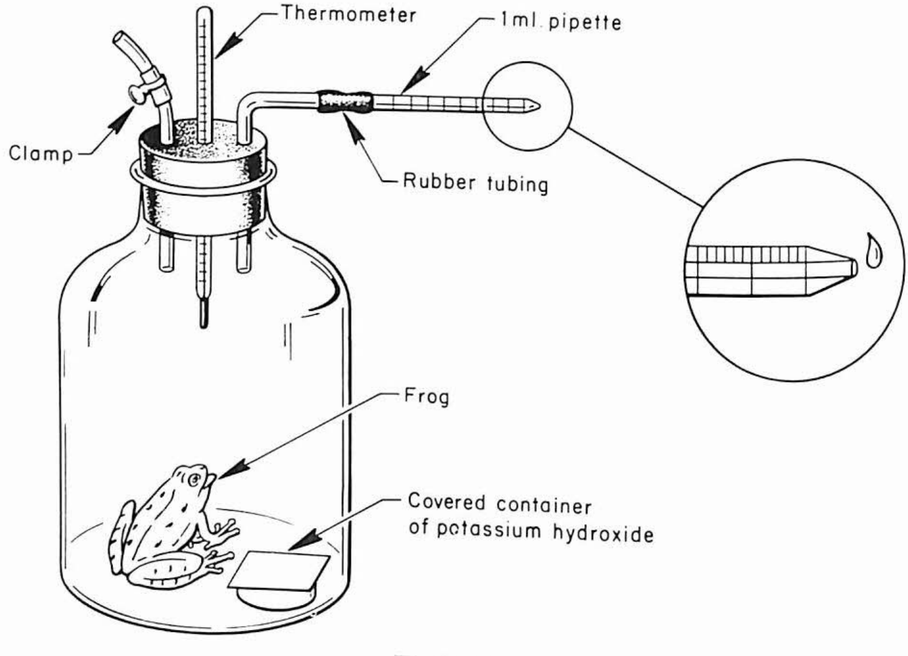

Figure 8

The experimental manipulations are not complicated, but they do require practice. The large container holds the laboratory animal—a frog—and a dish of potassium hydroxide, which absorbs carbon dioxide. Two tubes and a thermometer pass through the lid of this jar; the tubes (a manometer) measure changes in interior pressure. The thermometer will tell us about temperature changes, which may affect this pressure. The internal pressure of the system may be equalized with that of the atmosphere by use of a clamp on the vertical tube. The drop of oil, which is placed by touching it to the end of the horizontal tube, moves as the pressure of the system changes, providing that atmospheric pressure and temperature remain constant.

After the animal is placed in the jar, the pressures are equalized by first opening the vertical tube and then clamping it. The jar-animal system is now isolated from its environment, except through the intermediary manometer. Pressure changes within the jar cause the drop in the manometer tube to move. As a result, the total volume of the jar-animal system changes. If oxygen is removed from the system, internal pressure should decrease, and the drop will move toward the jar because external pressure is now greater than internal pressure. If the potassium hydroxide were to be omitted from the system, the total pressure change should be negligible, because carbon dioxide would replace the oxygen. The chemical equation for the reaction that occurs in respiration clearly indicates the equality of gas volumes:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + \text{Energy}$$

The potassium hydroxide, however, reacts with carbon dioxide according to this equation:

$$KOH + CO_2 \rightarrow KHCO_3$$

Therefore, if each unit volume of respired oxygen is converted into an equal volume of carbon dioxide, which is removed by reaction with potassium hydroxide, the rate at which the drop moves toward the container should be proportional to the rate of oxygen use.

Temperature must be recorded because the pressure and volume of gases are affected by temperature change. The rate at which the drop moves and the total decrease in volume of the system must also be recorded. From these data, the investigator should be able to determine not only whether or not oxygen is actually used by a laboratory animal and how rapidly it is used, but also the volume of respired oxygen.

Of course, this procedure is not without flaws, dubious assumptions, manipulative difficulties, and alternative possibilities. *Must* the experimental animals be frogs? For example, what other animals make good experimental objects? Are the results likely to be as good? What do we mean by "as good"? Would you anticipate the same rate of respiration? Is there a relationship between the weight of the experimental animal and the volume change? Is a one-frog experiment valid? How many repetitions and how many experimental subjects are necessary in order to arrive at some valid conclusion about oxygen intake in frogs? Does the water vapor produced in respiration affect the results? No control has been described for this experiment. How may such a control be added? Is it necessary for the purposes of this experiment to include a control?

There are physical problems to solve. What is the best way to attach the manometer tubes and thermometer? The authors have found that Sylastic rubber cement, a Dow-Corning product, works well. This cement combines flexibility with a tight air seal. Obviously, the system must be airtight if relatively small volume changes are encountered; there must be minimal leakage of air. The Sylastic cement provides this tight seal while allowing the tubes to be moved with some freedom.

Another physical problem is that the test animal must not come in contact with the potassium hydroxide, a caustic alkali. A small, firmly attached screen over the container of potassium hydroxide will be enough protection. Other physical difficulties in experimental design arise as the experiment is performed. Each may be surmounted if the functions of the experiment are considered. Certainly the system must be airtight. A convenient technique for inserting and removing the test animal must be mastered. The procedure for adjusting internal pressure must be reliable. Unanticipated problems will be encountered; each may be overcome by ingenuity and by reliance on the "rules" of scientific experimentation.

Having outlined the experimental procedure, we shall consider in greater detail the assumptions on which this experiment is based and on which its validity ultimately rests. One of these assumptions is that potassium hydroxide absorbs all the carbon dioxide which is excreted. If this is incorrect, interpretation of the data will be more difficult, because some allowance must be made for the unabsorbed gas.

Quantitative experiments with living organisms are complicated by the fact of life itself. Not only is each organism unique; each must be healthy and vigorous. It is much more difficult to manage a few laboratory animals than it is to handle the trillions of atoms in a gram of chemical substance. Experimental techniques must be mastered before meaningful data are collected. In quick succession, the animal is placed in the jar, fresh potassium hydroxide is added, the pressure is equalized, and the drop of liquid inserted into the manometer. During this time, the interchange of oxygen and carbon dioxide has already begun. Therefore, the experimenter must perfect his technique sufficiently so that mechanical and manipulative problems are minimal. Even elaborate and minutely outlined experimental directions often lead to frustration in a scheduled laboratory period, because there is too little time for the necessary practice in manipulation.

One experimenter may find it more convenient to insert the drop of liquid into the manometer, then place the animal in the container, then seal the top and equalize the pressure. Another person may first place the animal in the container. Whatever the choice, the ways in which these alternative techniques may affect the data should be explored.

One of the criteria for planning and performing biological experiments is that animals be treated humanely. Is this experiment humane? If the experimenter is genuinely concerned with maintaining an environment conducive to animal comfort, prior to, during, and after the experiment, he is humane. There is nothing in the experiment itself, if properly performed, that will endanger the safety of a laboratory animal. Of course, the container of potassium hydroxide must be firmly anchored and screened to eliminate the danger of contact. The animal should be removed from the container as soon as the data are collected, and returned to its cage. With these precautions, there can be no danger of cruelty.

The data may be recorded in any one of several ways. One of the most expedient, because of its simplicity, is a two-way chart in which one axis is time and the other is manometer readings. Changes in temperature may be noted when the manometer is read. The data may also be graphed. The volume of oxygen respired is related to the total change in the manometer reading. It may be calculated by this formula:

$$Vot = (0.21)\ (Vd)$$

where Vot = volume of oxygen in cubic centimeters used during the time t, 0.21 = the oxygen fraction of air, and Vd = volume decrease in cubic centimeters of total system.

Methods for calculating the total volume of the system and the decrease in volume are left for the student to devise. It is advisable that some estimate of error in measuring volume be made, in order to eliminate the possibility that observed changes are the result of measurement errors. Obviously, the smaller the volume of the total system, the greater the rate at which the manometer drop will move, and the greater the percentage of change in volume as a result of respiration.

The effect of temperature on the rate of respiration is another problem which will be encountered. What will happen if the temperature of the system is changed by either heating or cooling the outer container? If a mouse or rat were to be substituted for the frog, will there be an additional temperature change in the system?

Seed germination

After this experience with animal behavior, we turn to a somewhat similar investigation of plant behavior. The organism is the plant seed, and the behavior is its germination and subsequent growth. Many questions may be raised about seed germination. Does the position of the seed matter? What parts of the seed are necessary for germination? What environmental factors inhibit or accelerate germination? Are there significant differences in the rates of germination of different seeds?

These are but a few of the questions which may be investigated with simple experimental procedures. Consider, for example, the first question, about position of the seed. If the seed is placed upside down in an environment in which normal growth is possible, will its germination and growth conform to that of a seed planted right side up? In order for this question to have any meaning, "up" and "down" must be defined in some way, perhaps as a result of the physical characteristics of normal growth. Preliminary tests of seed germination should provide sufficient information for an empirical definition of "up" and "down."

Experimentally, it is not at all difficult to answer the second question. There are many different kinds of seeds, each of which has a covering of some kind, an embryo plant, and stored food. Therefore, in each seed there are structures and parts of structures which may be removed. In the case of the lima bean, which is botanically a seed, there may be seen within it a pair of "seed leaves," in which the food for the embryo is stored, the testa, which is the seed covering, and the embryo plant. Are the cotyledons, the seed leaves, necessary for germination, or do they serve some other function? What will happen if one of the cotyledons is removed? Does a lima bean whose right cotyledon has been removed germinate differently from one whose left cotyledon has been removed? What will happen if the seed coat is removed?

Students invariably suggest that water, light, and soil are essential for germination. Effective experiments for testing the effect of these environmental variables are quickly devised. These experiments may be elaborated by considering the effects of adding chemicals, such as salt, sugar, and fertilizers, to the water. Is air necessary? Will a seed germinate in water which has been boiled so that dissolved air has been removed? There is almost no end to the number of hypotheses about seed germination which may be proposed and tested in the laboratory without expensive or complex apparatus. Of course, each experiment must be controlled so that only one variable is examined, and so that some relationship between cause and effect may be discerned. How many seeds of each kind make up a reliable sample, so that the results are not attributable to such factors as defective seed or genetic variations?

Once germination has begun, plant growth is affected by many other variables. How much light must the plant receive? Is there a minimal light intensity for growth? Are there differences in the rate of growth with different kinds of light, or with different intensities? Figure 9 illustrates one experiment in which the effect of light direction on plant growth is tested.

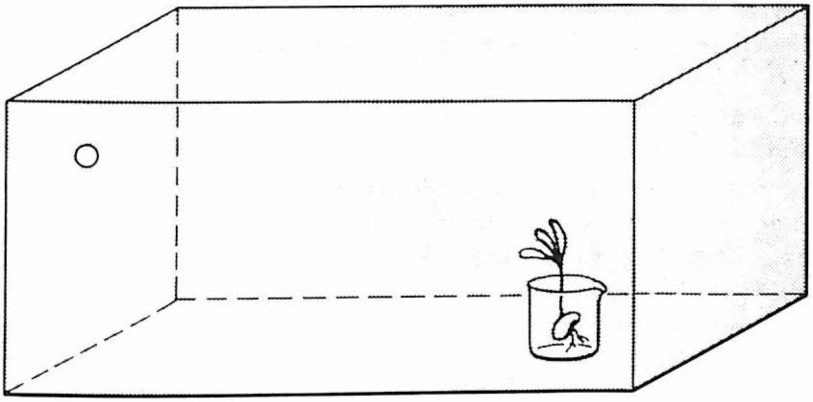

Figure 9

The box in which the plant is growing is dark, except for the light coming in from the hole in the side. If we assume that the limited air circulation within the box does not affect temperature, and if other factors are constant, the kind of growth which is obtained is presumably the result of the intensity *and* the direction of the light which illuminates the plant. Unless the experiment is properly controlled by means of another box, identical in every way except for the direction from which the light comes, it is difficult to justify the conclusion that plant growth is affected. Of course, if the experimenter has good reason to believe that the only important variable is the direction of light, then he may dispense with the control. Comparisons between different species of plants are conveniently made with this apparatus.

The knowledge obtained will be both interesting and informative. What is much more important, however, is that these experiments lead to growth in experience and skill in planning and carrying through real investigations. From a pedagogical point of view, the scientific facts and concepts which emerge from experimentation with seeds are, if not negligible, at least relatively unimpressive. True, these facts and concepts are fundamental to growth in understanding of certain biological schemes, and therefore to comprehension of the structure of science. But we must repeat that process, as exemplified by the kind of thinking and doing inherent in this crude scientific experimentation, is of much greater significance.

In order to enlarge on the role of the laboratory in Inquiry teaching, we restate one of the original questions as follows: "Will lima beans in which entire structures or parts of structures have been removed germinate as well as normal lima beans?" We will choose as our hypothesis the statement that "seeds which have been physically changed by removing some component part will germinate as well as unaltered seeds." "As well as" may be interpreted to mean as quickly, in approximately equal numbers, and with the same vigor. The structures to be removed may be one or both cotyledons, the testa, the embryo, or smaller segments of these structures. The samples should be representative and as nearly alike as possible. Random sampling helps to ensure homogeneity, providing that a sufficiently large quantity of lima beans is at hand and that selection is truly random. It is also possible to match the lima beans by inspection so that they are outwardly identical.

The experimental and normal seeds are planted under similar conditions. The time it takes for each seed to germinate should be supplemented with a continuous record of the height and rate of growth of the hypocotyl or of the roots (whichever is more convenient). According to the hypothesis, one would expect that, if unmutilated seeds germinate in approximately three days, the experimental seeds should take about the same time. If the altered seeds do not germinate in this time, the hypothesis is incorrect, providing that "as well as" means "as quickly." On the other hand, the conclusion that these seeds can not germinate at all because of their physical condition is unjustified. It may be that as much as ten days are required before any of these seeds sprout. Perhaps only a few will germinate in three days, a few more in five days, and none after that. Even if, as is likely, many of these altered seeds fail to germinate, it is not necessarily true that the injury to the seed is the real cause. The experimenter may have accidentally chosen defective seeds, or the growth conditions may have been sufficiently different to prevent sprouting. Repetition of the experiment with an increase in the sample size will increase confidence in the validity of the results, but it is unwise to expand conclusions beyond the experimental bounds. Even if the hypothesis is valid for the lima beans, it may not be valid for other kinds of seeds.

This experiment is rather unprecise and unsophisticated. The apparatus is almost starkly plain, uncomplicated by chemical tests or minutely quantitative measurements. Some measurements of growth rate may be made without difficulty, although the precision of measurement is surely not great. In order to evaluate the different hypotheses, it is probably sufficient to rely on semi-quantitatively or even qualitatively discernable growth differences.

Most of the assumptions which underlie this experiment have not been treated in detail. They relate to the energy of light which is absorbed in photosynthesis, the various media in which the seeds are germinated, sampling procedures, temperature effects, and adequacy of controls.

There are many desirable and practical explorations of plant behavior which do not yield quantitatively measurable data. Questions about the path of water conduction through stems or roots, leaf transpiration (evaporation through leaves), rate of leaf wilting, water loss in plants, swelling of seeds due to water absorption, excretion of carbon dioxide by plants, absorption of oxygen by seeds, and production of starch in plant leaves are examples of problems which may be better treated qualitatively than quantitatively.

Let us now consider this question: "What is the direction of movement of absorbed water in plant stems?" Figure 10 illustrates one experimental arrangement for finding an answer.

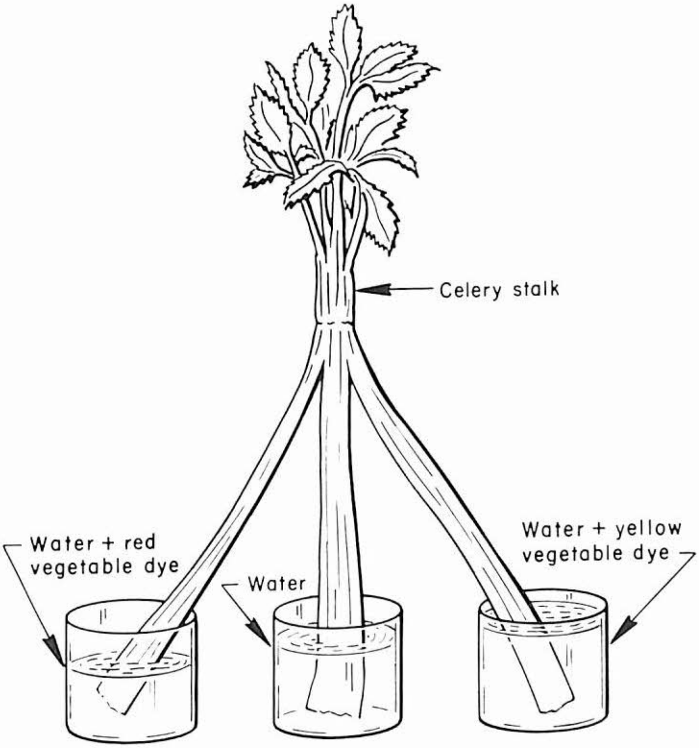

Figure 10

The hazards of experimentation with living organisms are well illustrated here. If the stem selected is a celery stalk (which is botanically not a stem), intake and movement of water is slow unless the stalk is fresh. The experiment may fail, and, unless the experimenter is both ingenious and knowledgeable, he will not know why. The cause of failure may be as "simple" as the decreased rate of water absorption because the celery is not fresh enough, or it may be the result of a much more complicated chain of events. To prescribe in minute detail the golden route to experimental success is to deprive the experimenter of much of the challenge and the value of experimentation. On the other hand, it is impractical for teachers and students to rediscover all knowledge, important and unimportant, on which the success of these experiments rests. We do not expect students to swim right from the beginning without a life-saving jacket. Therefore, we have suggested fresh celery in this experiment, and we have illustrated one kind of experimental apparatus for the purpose. Many other kinds of plant stems and roots may be tested in the same way.

Partially outlined investigations

An exercise in comparative anatomy We all know that the different species of fish in an aquarium are physically quite different. Gross characteristics such as size at maturity, color markings, location and shape of fins, and overall physical form enable us to separate the angelfish from the goldfish. More subtle differences include the way in which scales overlap, the number of rows of scales, the shape and appearance of the scales, the position of the eyes, and the relative size of the mouth. These external factors may be supplemented by study of internal structures and behavioral characteristics. Is the air bladder of comparable size in different species? Are their swimming motions comparable? Goldfish and guppies, which are roughly about the same size when young, are vastly different in size when mature. Is it possible that there is a normal range of size which is a distinguishing characteristic?

Additional questions may be asked: Is there any relationship between the number of appendages of fish and dogs? Does the fish have more or fewer appendages? Are these appendages alike in any way other than in function? Understanding of these and other characteristic differences is necessary in order to help differentiate scientifically between fish and dogs. We speak of differences, but there are also similarities, and it is often helpful in the scientific study of life to find the differences and similarities which are evidences of evolutionary process.

For example, let us select the earthworm, the crayfish, the frog, the fish, and the snake for study. There are both startling resemblances and substantial differences in their circulatory systems, and specifically in their blood color. Is there any observable difference in the color of their blood? If not, it is possible that they have a common coloring pigment. If, on the other hand, the blood of the crayfish is not red, it may be that the crayfish lacks this common pigment. Is it possible that the red coloring pigment of the frog and the snake is irrelevant and non-functional? Even in the animals with blood of the same color, there may be other significant differences. We suggest that the reader plan an experimental investigation of blood differences and similarities.

We may also look into the kinds of circulatory systems which these animals have. Not only is the blood color of the crayfish likely to be different from that of the fish, but the systems by which that blood is transported throughout the body are physically and physiologically different.

Comparative studies, however, need not come from post-mortem dissections, which require a high level of manipulative skill. Consider, for example, an investigation into the different kinds of fish scales, their shapes, and arrangements. This approach, so typical of the methods of nineteenth-century zoology, is as useful for the non-scientist today as it was one hundred years ago for scientists. The possibilities are almost endless. There are obvious differences between the hair of dogs and rabbits, as well as enormous variations between different breeds of dogs. Is beagle hair uniform in shape and color? Is there one preferred direction of growth? Is this direction the same on other beagles? Are there other characteristic features which will enable an investigator to identify a strand of beagle hair? Can you prepare an identification key for dog hair, so that, on the evidence of the hair alone, a positive identification may be made? In a somewhat romantic and far-fetched analogy, think of yourself as a detective, who, to solve a crime, must identify a few animal hairs. (How do you know they are non-human?)

The suggestions for investigation in this section do not satisfy the criteria for scientific experimentation. They are studies in comparative anatomy, whose data come from close observation. They are descriptive, but their importance is not diminished for this reason. Ideas of causation are scientifically testable by experimentation, but these ideas spring from the knowledge of the world which comes from the work of observers and comparers. Differences *and* similarities exist throughout life, and the possibilities for firsthand investigation of variation and uniformity are endless. These problems are merely suggestive. Some are not easy. They all require time, effort, and thought. But each is a genuine, if minor, problem, which will repay the investigator with a dividend of genuine knowledge and an increment in Inquiry skill.

The relationship of structure and function is frequently enigmatic. There is often no apparent advantage to the organism in some structural organization. It may be difficult to attribute variations in the arrangement of fish scales or in the orientation of animal hair to functional differences. In a general sense, each organism has "solved" its environmental problems and is adapted for its particular mode of life. Specifically, however, the results which are obtained in the comparative studies suggested above may often seem to be unrelated to problems in adaptation and function.

An experimental investigation of fly behavior—reaction to heat and light Where do the house flies that buzz around the porch on a warm winter day come from? Winter is not the usual season for fly breeding, and unless the warm spell is prolonged, it is inconceivable that breeding has occurred. Still, the buzzing fly is no figment of the imagination. Where does it come from? Is it possible that houseflies which survive winter temperatures are animated by the sun's warmth?

One of the most interesting and practicable insect experiments is to test the effects of temperature and light on insect reactions. An experimental apparatus such as that in Figure 11 is helpful in qualitatively investigating the influence of temperature and light.

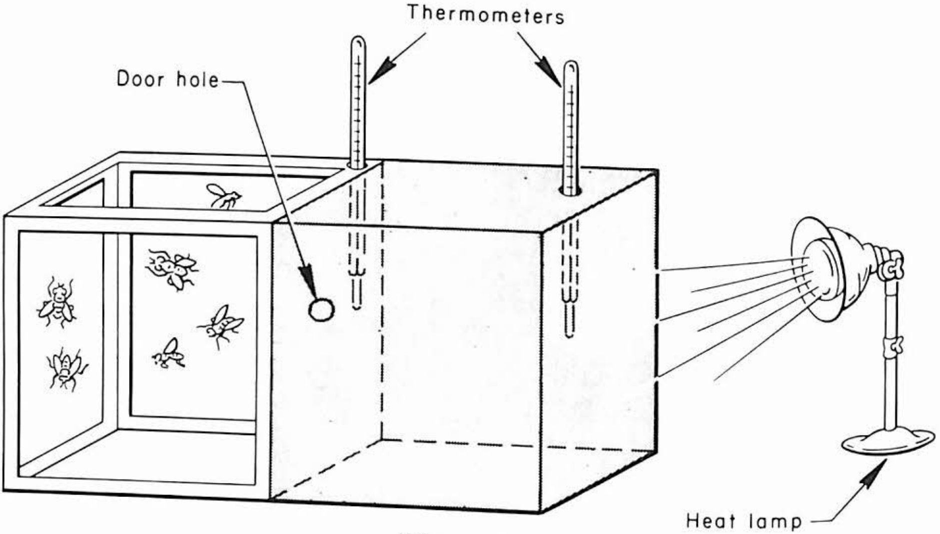

Figure 11

Do flies "prefer" darkness to light? A high to a low temperature? High temperature and darkness, to high temperature and light? What other questions can you test with this or a similar apparatus? How will you plan this series of experiments so that valid and reliable results are likely to be obtained? How can these results be verified? What are the assumptions on which validity rests? Do the facts and conclusions suggest an answer to the original vaguely worded question about the emergence of house flies in winter?

Chicken feed A medium-rare prime steak, a baked Idaho potato, tossed salad, and home-made apple pie—these words evoke certain delightful gustatory connotations. The thought of a dinner in which these foods are ground together into an undistinguishable paste is almost sacrilegious. Nutritionally, however, there is little difference. Human beings are plainly creatures whose appetite is conditioned by taste, odor, and color preferences. Household pets share some of these preferences, in addition to exhibiting idiosyncrasies of their own. No one knowingly gives his dog a carrot in place of a steak bone.

Let us assume that we do not know which foods a bird like the chicken prefers. Is there any way by which these preferences may be discovered? Are chickens omnivorous? (Is beak shape any indicator of food habits?) We know, of course, that commercially grown fowl are usually fed on grain. Are all grains equally appetizing? Does the color of the grain make any difference? What will happen if chicken feed dyed with a harmless vegetable coloring is fed to chicks? A similar investigation is easily made during the winter season at an outdoor feeding station.

What are some of the variables which must be recognized in this food preference study? How are the data to be collected and classified? Is it likely that the same scheme will be equally convenient for both chickens and "backyard" birds? What kind of feeding container is best? Will its design affect the results? Suppose that red-dyed grain in the feeder disappears quickly. Is it legitimate to assume that birds prefer red? Has the possibility of interference by other animals been excluded? Squirrels are excellent climbers, and it may be that it is they, not the birds, that the investigator has fed. Pitfalls and traps for the unwary abound in experimentation with animals, especially when experimentation is attempted without the proper controls. For example, the attractiveness of the grain, colored or not, may depend far more on the availability of natural food than on the color or palatability of the grain. It is imperative that the experimenter study his techniques carefully, in order to pick out the assumptions on which his conclusions must eventually rest. It is just as important that the experimenter remain uncommitted to any particular procedure or hypothesis. He should feel free to change the experimental design in testing his hypotheses. Whatever his results, their worth is directly proportional to the care which he has taken to eliminate extraneous variables, and the recognition of possible influences which he cannot exclude. We do not pretend that it is important, in any substantive sense, for students to learn that chicks prefer one kind of grain to another. The exercise of experimental imagination and ingenuity, the continued practice of sound investigative habits and skills, and the constant interaction of the mind with the stubbornly hidden facts of nature is what gives meaning and value to an education in science.

A microcosm Green plants remove vast amounts of carbon dioxide from the atmosphere every day, returning in its place approximately the same volume of oxygen. (Plants, of course, also use oxygen and give off carbon dioxide.) Animals, on the other hand, respire oxygen and excrete carbon dioxide. The production and consumption of carbon dioxide and oxygen are roughly matched, and therefore the relative percentage of each component in the atmosphere remains nearly constant.

This equilibrium may be duplicated by sealing one or two small animals and a sufficient number of green plants in a container. This environment, sometimes called a microcosm, is an elegant yet unsophisticated experiment with life forms. Figure 12 is of one kind of microcosm.

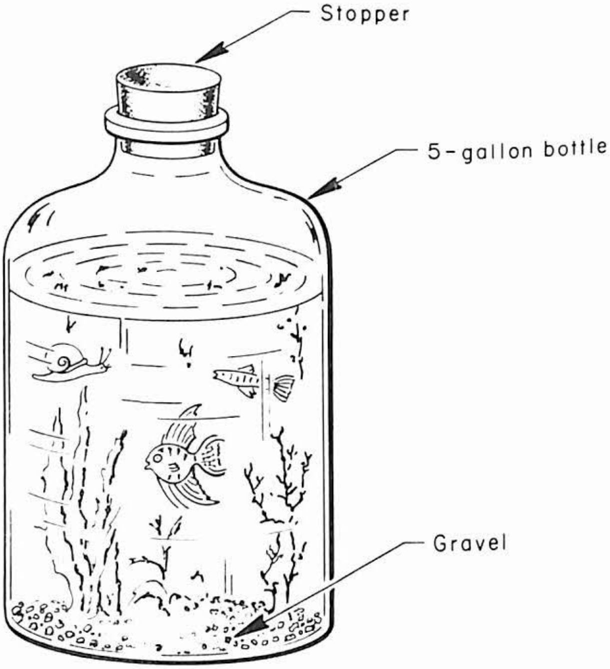

Figure 12

Once the system is well established, with healthy inhabitants, it is possible to study some of the dynamics of "natural" systems. What questions, experimentally testable with this or some similar apparatus, come to mind? Must the data be qualitative? If not, how may they be quantified? The student should investigate at least one hypothesis about the interrelationships of the plants and animals in his microcosm. In his laboratory report, the difficulties and assumptions should be clearly specified, controls analyzed for their adequacy, assumptions and errors pointed out. For example, how long is the experiment to take? To what extent is the outcome of the experiment determined by laboratory conditions? By the container? By the water supply? By the seal, which presumably separates the system from the room?

What new questions that come out of this experiment are worth investigating? What modifications in the experiment can you suggest for further study?

Transpiration In order for plants to grow, they must continually transfer water and water-dissolved nutrients into their tissues from the soil in which the plants are imbedded. Some of this water passes completely through the plant, escaping from the leaves. This loss of water is known as "transpiration." The rate of transpiration under more or less identical conditions varies with the plant species. It is not unusual for an oak tree to transpire hundreds of gallons of water in a week. On the other hand, a geranium plant transpires much less water in the same time. Is this caused by the much smaller leaf area of the geranium or is it a species difference? Unfortunately, the experimental study of plant transpiration is more difficult than experimentation with many of the biological phenomena with which we have been concerned. Even if it is possible to equate leaf areas of two different plant species under "identical" conditions, experimental rigor is not guaranteed. The demands of the experiment may affect the transpiration rate of each species differently, so that misleading results are obtained.

One of the first problems is that of matching the surface areas through which transpiration occurs. If it is assumed that surface area is proportional to the weight of stem and leaves, the surface areas of the experimental plants can be indirectly calculated by weighing their stems and leaves. The observed loss of water by each plant is then reduced to a value commensurate with its "surface area." This assumption is perilous at best. If transpiration occurs mainly through the leaves, heavy plants will be assigned much greater "surface areas" with this method than is correct. It may be better, although less convenient, to remove and weigh the leaves or to calculate the total surface area. (Is it necessary to measure the surface area of each leaf?) Comparisons of transpiration rate based on these data are more likely to be relevant than are comparisons based on weight alone. But this method is also subject to some uncertainty, and the investigator should think through his assumptions and the inevitable errors of experimentation.

The apparatus itself (see Figure 13) is relatively simple, and many different versions have been employed by botanists in the past.

The plant is sealed into one side of the apparatus, the other side remaining open. The tube connecting these two sections is filled with water. Hopefully, the plant maintains a more or less normal existence, absorbing water through its vascular system, raising the water through the stem, and transpiring the excess through its leaves. The amount of

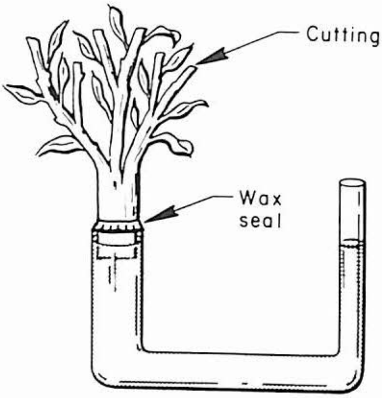

Figure 13

water lost in transpiration and in the other normal metabolic processes of the plant is presumably equal to the drop in water level of the side tube. Of course, some new problems will confront the experimenter. How can he distinguish between transpiration loss and metabolic use? To what extent is the drop in water level the result of evaporation from the open tube? Is there any way of eliminating evaporation as a source of confusion?

The experiment should be carefully planned; the procedures, assumptions, data recording, hypotheses, and conclusions searched through for weaknesses and fallacies. There should emerge at the conclusion of this experiment one or more follow-up activities, whose function is both verification and strengthening of skill in Inquiry.

The earth sciences

Metaphorically, the earth sciences are a scientific collage. They are a rather dissimilar collection of non-biological, non-chemico-physical disciplines, which has been christened "the earth sciences" in the hope that this all-inclusive name will breed unity. The individual sciences are distinct entities: astronomy, geology, meteorology, and oceanography. If there is a unifying structure, it arises from physical principles which explain the different phenomena of the earth—its interior, surface, and place in space. These sciences in their collective incarnation as the earth sciences are still primarily descriptive, although vast strides have been made in establishing them on a firm theoretical framework. As a rule, experimentation in the earth sciences is much more difficult to carry out than in the physical sciences. Experimentation is limited to manipulation of physical and chemical phenomena, which, guided by theoretical models of the mass phenomena of the earth sciences, are tested for relevance. For example, in order to study the process of cloud formation, it is desirable to form clouds at will under appropriate experimental conditions. Unfortunately, clouds are not yet responsive to man's commands, and, therefore, laboratory experimentation is understandably obstructed. As B. J. Mason, Professor of Cloud Physics at the University of London, remarks:[1]

> There are serious difficulties in attempting to simulate cloud formation in the laboratory largely because it is impossible to scale down all the physical quantities in the correct proportions and because of the disturbing influences of the walls of the containing apparatus. Nevertheless, some valuable clues on the manner of cloud formation and evolution may be obtained from model experiments even though they cannot reproduce the natural conditions in all respects.

A very similar situation is found in the case of earthquakes, volcanic eruptions, and ocean currents. It is only natural, therefore, that some of the experiments in the earth sciences which are proposed in this book are not experiments at all. The experiments and descriptive investigations which follow tend to be less precise and of less relevance to the larger world than those which have been previously encountered in the physical and biological sciences. They are more illustrative, more observational, longer in duration, and less controllable. The variables and their effects are more difficult to control and to relate to hypotheses, and definitive experiments to test hypotheses are more uncommon.

Temperature – summer and winter

One of the perplexing facts which children in the northern hemisphere encounter is that in summer, when temperatures are high, the earth is several million miles farther from the sun than in winter. This seems so contrary to common sense that children often refuse to accept it. It seems obvious that the farther away a body is from a source of heat, the less heat it receives. Children often are unable to relate the angle of the earth's axis to the plane of the ecliptic, and the resulting seasonal changes to heat absorption. The qualifying phrase, northern hemisphere, was inserted in the beginning sentence of this paragraph. Is this qualification necessary? What are the normal temperatures which prevail in the southern hemisphere during the northern summer? During the winter? Why should these temperatures differ from temperatures in the northern hemisphere? Are temperatures contingent on the length of the day?

In order to investigate these questions, other questions are proposed. What are the relative lengths of daylight and night during the summer and winter in each hemisphere? At the equator? Does the sun rise over the same point on the eastern horizon each morning? Does it set over the same point on the western horizon each evening? These questions are related in that their explanations will be based on the apparent motion of the sun and on the earth's orientation in space. These explanations are scientific because they are derived from a general theory, a number of independent, verifiable facts, and one or more assumptions.

These questions may be answered by gathering observational data. During the year, as the location of the point at which the sun rises and sets is noted, it soon becomes apparent that the point of rising and setting changes. If, in spring, the sun rises each day farther and farther to the north, the path of the sun through the sky will change accordingly, rising ever higher in the sky. The observer will find that the exact clock time at which the sun reaches its zenith is usually not noon, and that this zenith position differs from day to day. Therefore, because the sun is farther north in May than in November, the angle at which the rays of the sun strike the earth should be correspondingly different. The shadow cast by a fixed object should change length and direction if it is periodically observed at the same clock time.

Comparison of the length, area, and direction of such a shadow over several months gives direct knowledge of the apparent movement of the sun and of the distribution of the light which strikes the earth. The apparatus illustrated in Figure 14 is a simple device for gathering the appropriate data.

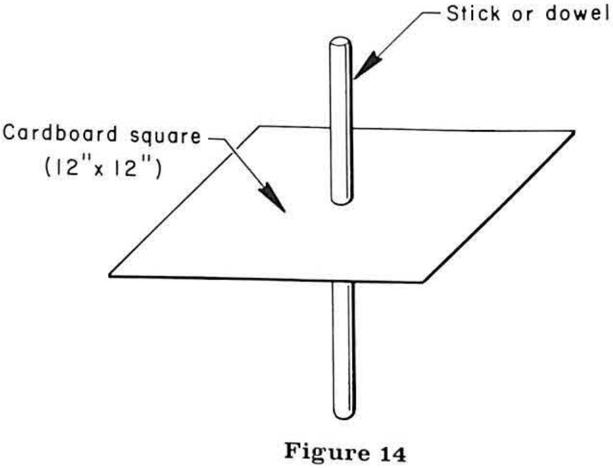

Figure 14

If a card one foot square is held in the sun so that the dowel casts no shadow on the card, the card should be perpendicular to the sun's rays. (The experimenter is cautioned *not* to look directly at the sun at any time unless his eyes are properly shielded.) The size of the shadow cast by the card is a function of the area of the card, the time of day, and the angle at which the rays hit the earth. As the sun's position changes, the orientation of the card remaining constant, the size of the shadow changes. Of course, the distance of the card from the ground must not be changed, lest the size of the shadow be affected. If, during the summer months, the shadow is smaller than during the winter months, this is presumably because the angle of the sun's rays has changed. Assuming that the column of light falling on the card is constant, the smaller summer shadow, the equivalent of the total light area which would fall on the ground were the card not in the way, must represent a greater concentration of light than the larger shadow of the winter. If the heat which strikes the ground is proportional to the area of shadow (and therefore of light), the dilution of light over a greater area in winter must result in a decreased concentration of heat per unit area of light-heat striking the ground. Assuming again that the difference of approximately three million miles in the earth-sun distance is insignificant compared to the effect of angle change, we are now in a position to explain tentatively why summer is hotter than winter. Certainly it is reasonable to suppose that the light-heat which strikes the earth at our latitude is more concentrated, and, as a result, the ground is heated more effectively. The difference in earth-sun distance in the course of a year is approximately three percent. Is it justifiable to neglect this variable in explaining summer and winter temperatures?

An interesting variation of this experiment is to determine the actual change of the sun's position during the year. For example, on September 21, the sun, at latitude forty-one degrees north, is at a noon altitude from the horizon of approximately forty-nine degrees. What will the altitude of the sun be on December 10? To find out, the apparatus of the preceding experiment may be modified by pushing a four-foot dowel (this length is not critical) through the card so that only a few inches of the dowel protrude through the top of the card. Now, when this card-dowel is oriented to the sun so that the dowel above the card casts no shadow and the other end of the dowel touches the ground, the angle between the ground and the dowel is easily measured. This angle is the altitude of the sun.

Of course, the experimenter should be aware of the effect of arbitrary time changes, such as daylight saving time, on the time of observation. He should also know of the apparent seasonal change in the sun's velocity as it moves through the sky. For example, in mid-February, clock time is more than fourteen minutes ahead of the sun, whereas in early November, the clock is more than sixteen minutes behind the sun. Are these time differences likely to affect experimental results significantly? What errors in measurement are inescapable with the procedures outlined above? Within what limits should the results be expressed in order to take these errors into account? In addition to the assumptions already presented, what other assumptions are relevant?

Deposition of sediments

One of the important rock forming processes is that of sedimentation, in which eroded and weathered rock materials are transported, usually by running water. In time, this rock debris is squeezed and compressed into sedimentary rocks. This process of transportation and deposition may be studied in miniature, and, within limits, the miniature is analogous to the natural course of sedimentary rock formation which geologists have proposed.

The problem to be investigated in this section is to correlate the water distribution of rock materials with the size of the individual rock particles. The size of the particles will presumably have something to do with the distance to which these particles are carried by a stream of water. By testing different kinds of particles under controlled conditions, it should be possible to estimate the relative distances that these particles are carried, and to discern, at least qualitatively, the effect of size on the distance that they are carried.

We suggest collecting at least half a dozen samples of different-size rock materials, ranging from pebbles of about three-sixteenths of an inch in diameter to fine sand or silt, each size stored in a separate container. Of course, even though the particles are of approximately the same size, they may differ in density or shape, so that in no case will individual samples be identical.

The experimental design suggested for this investigation is pictured in Figure 15.

The trough is narrower at the top than at the bottom. The water flowing in at the top carries the particles to a distance which depends on the particles themselves, the slope, the velocity, and the volume of water. Since slope, velocity, and volume are constant, the distance should depend on the particles alone. Each sample is dropped into the stream through the funnel, and flows to the plastic sheet at the base. Nothing in this experiment requires unusual or expensive apparatus, nor is it necessary to use this particular apparatus if a simpler or more convenient design can be constructed.

The first question to be tested may be, "Are particles of different sizes and compositions carried equally far by a current of water?" One may hypothesize that small particles will be carried farther than will large particles. A second hypothesis may be that as the velocity of the water is increased, all particles are carried farther. To this proposition, there may be appended the subsidiary hypothesis that a larger flow of water at the same velocity will cause the particles to move farther. It is also possible to contrast the effect of a small volume of water, moving at a high speed, with the effect of a large volume at a lower speed.

In order for this experiment to be predictive, the results obtained should be relevant to field problems. That is, natural rock-carrying processes should also depend on such factors as velocity, total flow, particle size, and slope. A field trip to investigate such natural processes will be of great interest and value following such an experiment. Or a field study of sediment distribution may be conducted prior to the experiment. In this case, the experiment is transmuted into an explanation of the phenomena observed in the field. As previously suggested, it may be necessary to assume that each sample is homogeneous, an assumption which is open to question. It may be necessary to ascertain the average size or average density of the samples experimentally.

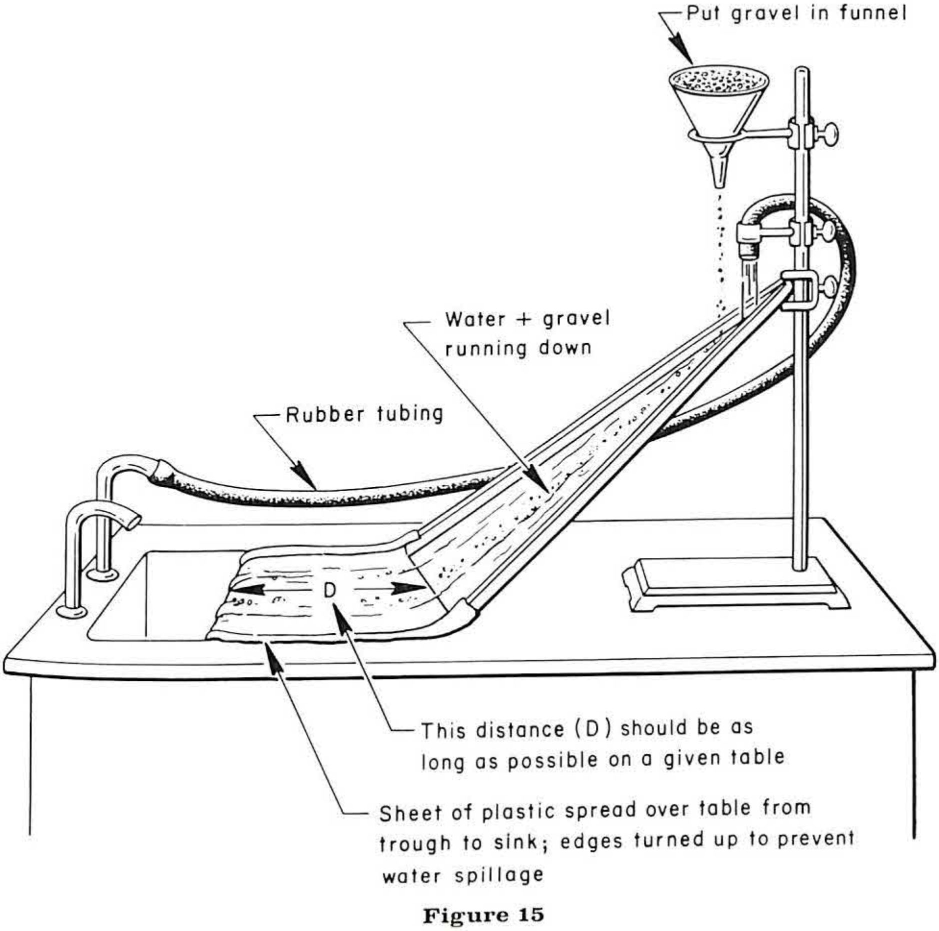
Put gravel in funnel
Water + gravel running down
Rubber tubing
D
This distance (D) should be as long as possible on a given table
Sheet of plastic spread over table from trough to sink; edges turned up to prevent water spillage

Figure 15

Suitable procedures are left for the reader to work out. Still another assumption with which the experimenter must grapple is that, in the course of each experimental run, the water velocity is constant. It is possible to test the validity of this assumption by comparing, at predetermined intervals, the number of seconds required to fill a jar of known volume.

The rate of settling of soils in water

The investigation suggested in this section is a variation of the preceding experiment. The major difference is that the variable of running water is eliminated, and, therefore, experimental technique is simplified. If a number of soil samples of different kinds, such as sand, gravel, loam, silt, and clay, are thoroughly shaken in water and allowed to settle, there is a noticeable difference in the rate of settling of the various soil components and in the final composition of the soil layers. These differences should lead to a tentative relationship between the various settling rates of these soils and their composition. It will be necessary to try jars of different sizes and different water volumes in order to obtain verifiable results within a reasonable time.

The conclusions should be helpful in understanding how sedimentary rocks are formed. Appropriate field trips, films, or slides will be useful in pointing up these applications. Of course, this "duplication" in miniature of natural processes is brimful of assumptions, both implicit and explicit, which should be exposed in order to limit conclusions to their proper bounds.

Mineral taxonomy

One of the most fascinating science hobbies is mineral collecting. Few children, or adults for that matter, can refrain from taking home an unusual rock or mineral if they chance to find it. The identification of minerals provides a splendid opportunity to investigate the taxonomic realm of the sciences, a descriptive endeavor which has been of the greatest importance to each science in its early years, and one which is still unfinished in many of the sciences. Nomenclature *is* important. For example, to the mineralogist, the name "calcite" conveys the information that the mineral referred to is $CaCO_3$, with a specific gravity of 2.7, a hardness low enough to be scratched by a brass pin, a generally white or yellowish appearance, a hexagonal structure, and cleavage into rhomb-shaped fragments.

The following characteristics are usually sufficient for the beginner to devise a scheme by which many minerals may be identified: color, luster, hardness, streak, cleavage, fracture, specific gravity, and magnetic properties. It is not our intention to require the beginner to identify unknown minerals by means of these characteristics, but rather to enable him to learn how mineralogists devise such a scheme. For this reason, there should be available a number of labeled mineral samples for study, so that the student can, from his own direct manipulation and observation, formulate such a taxonomy. These specimens should be "typical" in that they should be like museum specimens. If they are not carefully selected, the student will soon discover that he cannot identify many of the minerals, depending on the conditions under which they were formed and under which they existed. We suggest that these minerals be included: halite, quartz, olivine, mica (both muscovite and biotite), orthoclase feldspar, albite, calcite, galena, pyrite, gypsum, magnetite, sulfur, corundum, azurite, fluorite, graphite, coal, garnet, hematite, talc, and siderite.

Although the selected physical characteristics are usually sufficient to identify these and many other minerals, it is often necessary for mineralogists to resort to chemical tests and other types of analysis, particularly when the minerals are present in minute quantities or are intermixed in some complex way. For the purposes of this experiment, however, it is sufficient for the student to prepare a reliable taxonomic scheme based on the few physical properties described above.

For further study

1. Write a critique of the rusty-nail, the heat-loss, and other experiments, pointing out unrecognized assumptions, possible sources of error and methodological errors.
2. Develop in detail one of the partially complete experimental designs in this chapter.
3. Adapt one of these designs for an intermediate-grade elementary school classroom.
4. Classify each of the experiments in this chapter according to the schemes and themes to which it is related.
5. Plan experiments based on the following schemes:
    (a) There is a maximum average size for each kind of plant and animal.
    (b) A magnet always has at least two poles, which are surrounded by a force field.

References

1. Mason, B. J., *Clouds, Rain, and Rainmaking* (Cambridge: Cambridge University Press, 1962), pp. 12–13.

The child's success in learning science is, to a large extent, the result of careful and imaginative teacher planning. Educators have always stressed the importance of planning, as the number of formalized techniques and planning aids testifies. Two of the best-known planning devices are the curriculum guide and the daily lesson plan.

Curriculum guides are often written on a city or a regional basis by selected staff members; in many cases, they are close copies of the textbook series that has been adopted by the school system. Tying a curriculum to a particular textbook immediately decreases the flexibility of long-term planning. The daily lesson plans to which this kind of curriculum lends itself transfer a built-in rigidity to the classroom; they become diaries in which the teacher records the content of the curriculum guide and the textbook to which her children have been exposed. Perhaps this criticism is somewhat overdone, but these perils do exist. Both long- and short-term planning must be grounded on a better rationale than that of conforming to a course of study.

A more reasonable view of the function of curriculum guides is that, although they too possess a potential for guiding and assisting teachers to plan the year's work, the professional teacher must not abdicate his own responsibility for selecting the objectives and the schemes with which he and his class will be engaged. The teacher becomes personally involved by direct participation in long-term planning. Clearly, then, the curriculum guide must serve only as a *guide*.

13

Planning for teaching

A basis for planning

Successful planning is predicated on clear-cut, sharply defined objectives which learners can reasonably achieve. It is helpful to divide objectives into two broad categories: overall and specific. Overall objectives are the indeterminate, general functions of science education. Specific objectives are the short-term, more or less immediately attainable skills, abilities, and competencies. The following are examples of overall objectives:

1. To foster the growth of the inquiring mind.
2. To learn the facts and principles of the sciences, which are important in modern living.

These objectives are not immediately achieved in any single learning experience. They are, however, significant in setting the tone for the daily lessons. They are even more useful if some estimate of their relative importance is made, for the purpose of evaluating educational experiences. If, for instance, the first objective cited above is classified as primary, very few verification experiments will be included unless they somehow foster this kind of independent thinking. Because it is a primary objective, "the inquiring mind" also serves as a criterion for evaluating methodology. The teacher may ask herself such questions as, "Does a *demonstration* of a scientific principle best achieve this goal, or should the principle be investigated as a laboratory problem?" Within the confines of the subject matter selected, the answer must lead to the primary objectives. If not, other subject matter should be chosen. By these daily decisions, planning is continually referred to the prime objectives.

Some suggestions for formulating leading questions for learners are given later in this chapter. However, the relationship of such questions to the primary objectives should be briefly described. The particular questions asked by learners and by teachers are perhaps the single most important avenue of communication in the teaching-learning process. Not all kinds of questions, however, are equally relevant in achieving the goals which are desired. A child who is asked to name three classes of rocks and their modes of formation can hardly be expected to answer correctly by his own reasoning or experimental investigation. On the other hand, a question about the factors which affect the rate of seed germination can elicit desirable patterns of thought because of the information about plant growth which children have already accumulated. Questions and their answers are naturally dependent on well-designed laboratory experiences and skillful guidance. The latter question is almost self-answering. It contains within itself the potential for finding answers by procedures which are compatible with prime objectives. The second overall objective which was listed, learning facts and principles, is classified by the authors as a secondary objective. This is not meant to imply that the accumulation of facts is necessarily unimportant, but rather that it is a goal to be achieved indirectly. Essential facts are sought by experimentation and observation. They are found in reference sources, audiovisual aids, and in prior knowledge. They are learned because they are meaningful and useful in finding answers.

The implications of this philosophy for daily planning are clear. Make-work assignments to "draw and label the parts of the flower according to the textbook diagram," which are intended to reinforce factual learning, should be avoided because they are sterile and boring. Questions such as these are more promising: "Find as many ways as you can in which these rocks differ from one another. In what ways are they alike? How *many* different ways can you find in which they are alike? Different?" The necessary factual material is gathered for a purpose! Specific information gained in this way seems to have a better chance of survival, but even if it is retained no longer than information learned by traditional methods, the change in emphasis should lead to greater interest and enjoyment. Although enjoyment, of itself, should not be the sole criterion for studying science, neither should it be ignored. Reluctant learning, whatever the reason, is diminished learning.

Another factor which must be considered in selecting specific information is the possible submergence of ideas in a sea of facts. It is difficult for a student to extract general principles from an exercise laden with trivia. For these reasons, specific information should be carefully selected, although the exact facts which may emerge from inquiry are not easy to predict. An excessive number of facts tends to detract from their significance, yet too few cannot lead to the general ideas and principles which are sought. The proper balance of significant information to be included in a lesson is difficult to predetermine. Frequent assessment of the children's progress after initial planning seems to be the most reasonable method of achieving this kind of balance.

Behavioral objectives

A strong educational foundation on which to plan is formed from the behavioral abilities that students can gain through any given exercise, experiment, or study. When behavioral objectives underlie classroom activities, the teacher must ask what specific skills, abilities, understanding, and information a learner might achieve as an outcome of the lesson. With these questions as a guide, the remainder of the plan must be developed according to each of the behavioral objectives. The behavioral objectives below are taken from the AAAS materials reviewed in Chapter 6. The number of selections is large in order to show many kinds of behavioral objectives for different cognitive levels, varying schemes, and a broad spectrum of subject areas. The selections have been made at random; hence there is no continuity from one to another, nor is there any reference to the specific lesson for which they have been designed. Each example begins with a phrase such as "At the end of the experiment the child should be able to..."

1. Distinguish between two temperatures without the aid of a thermometer where large differences in temperature exist.
2. Distinguish between the temperature in one place and that in another place with the use of the color-coded thermometer.
3. Identify various sets of objects when given the names or characteristics of the members.
4. Separate or classify the objects according to characteristics specified by the teacher.
5. Construct a classification of a set of objects into two or more groups depending on whether the objects can or cannot be used in a stated way.
6. Distinguish among certain objects by odor characteristics.
7. Demonstrate that some body forms of animals can be described in terms of three-dimensional shapes.
8. Identify from a group of materials those that can support the growth of molds, and those that do not support such growth.
9. State and demonstrate which of two angles is larger by superimposing one angle upon another.
10. Demonstrate the measurement of the *same distance* in two ways, using different measuring instruments or units (for example, number of steps in a stick).
11. Distinguish and name an unseen three-dimensional object from two-dimensional projections (shadows) of it.
12. Demonstrate and state, in appropriate units, the speed (distance traveled per unit of time) of objects placed at different distances from the center of a rotating disk.
13. Identify the single variable under study, given a statement to be tested.
14. Observe an object of a certain length or width and name a known object which is approximately the same length or width.
15. Distinguish between a statement based on direct observation and one that is an inference from observation.
16. Extrapolate from a given line graph.
17. Construct a classification of objects by using at least one series of subjects.
18. Demonstrate the classification of materials as conductors or nonconductors with the use of an electric circuit.

19. Identify factors in an environment which may affect an organism that grows on any medium.
20. Identify the variables which might affect a cylinder's speed as it rolls down an inclined plane.
21. Identify true north from a shadow path.
22. Name and distinguish between the heights on the indicated contour map.
23. Identify points on an x-y plane and draw a smooth curve through the points to portray the quantitative relations.
24. Construct and demonstrate an experiment from which they can collect data to answer a question about photosynthesis.
25. Describe the characteristics of an operational definition of the relative brightnesses of the components of an eclipsing variable star.

These behavioral objectives are used in experiments which are given such process titles as Classifying 1, Inferring 4, Using Space-Time Relations 5. All fourteen volumes of the AAAS materials contain serially numbered experiments whose titles state the specific areas of study. Although the experiments have not been arranged consecutively in the printed manual, for various reasons, the role of the title as a general objective is obvious. The series attempts to develop concepts in classification, communication, measurement, use of numbers, observation, space-time relations, prediction, inference, and interpretation of data, among others. The topics as indicated in the process-title of each experiment or study are subject-matter objectives and are followed by behavioral objectives such as those given above. In designing this curriculum, the AAAS writers have considered two major factors. The titles indicate concern over *what is to be taught*, in terms of the broad categories or themes which underlie all of the sciences. Subject-matter areas selected to exploit these themes are chosen from many different scientific disciplines. It should be pointed out here that successful use of these materials is dependent on the teacher's broad knowledge of science or his willingness to prepare thoroughly.

The second factor considered by the AAAS writers is indicated by the behavioral objectives stated at the beginning of each experiment. The concern is that *what is to be taught* should be the same as *what is to be learned*. The behavioral objectives become the "what is to be taught," because the experiment is designed to achieve the objectives directly. These objectives then become quite useful for teachers as guide lines for achieving the proposed goals.

In many traditional curricular designs, the objectives for the learner differ appreciably from what is actually learned. This difference is usually not evident, because evaluation of student performance is neither based on the objectives nor compatible with them. The stated objective may be "developing an understanding of the photosynthesis process," whereas the evaluation of student accomplishment of the objective is based on the ability to "name the steps in the process of photosynthesis." There is no evidence that the ability to "name the steps" implies an understanding of photosynthesis.

In the AAAS program, however, the evaluation is developed specifically in terms of the objectives. Evaluation and behavioral objectives are in a sense synonymous, and it is difficult to characterize the following statement as an initial objective rather than as an evaluative device: "State whether the image formed by a pinhole will be larger or smaller than the object, depending upon the relative location of the pinhole."

To exemplify further, let us look at "Experimenting 2" from the AAAS program. One of the objectives given is the preceding example. The appraisal exercise follows: "Tell the children that you propose to move the projector back from the screen two decimeters. What will the image size be then? Will the image fit on the screen?" Here it is clear that if the child's response to the appraisal question is acceptable the objective has been achieved. One can then claim, perhaps overconfidently, that what was to be taught is the same as what has been learned.

Long-range planning

At first glance, it seems that an authoritative source, such as the local science supervisor or science consultant, should determine what to teach during the academic year. These positions are held by people whose knowledge of science and education makes them specialists in the field of designing school-wide programs for educating students in various aspects of science. Their guidance at each grade level stimulates the development of integrated programs. The specialist must account for the significant factors of the sciences and of children which insure a meaningful program. Unfortunately, most school systems cannot afford to employ a specialist to guide the classroom teacher in science. Indeed, if all schools could employ specialists, there would not be enough qualified personnel to fill the positions. It appears, therefore, that needed leadership must come from the institutions of higher learning. Despite the fundamental differences which are evident in the new programs, each reflects the thinking of the most able people in the field. The classroom teacher, then, either as an individual or as a curriculum-committee member, must adopt these materials for her school. Planning by a teacher committee, working with a science-education specialist, may be arduous and time-consuming. On the other hand, planning may be nothing more than adopting one of the major national programs in its entirety. In any event, the translation of the yearly planning into daily activities must continue to be the responsibility of the classroom teacher.

Daily planning

Once the process and product themes have been selected, the teacher is confronted by the immediate problems of how to implement the teaching-learning process most effectively. What methods are best used? Which materials are needed? Are they available? How can the students best be motivated? What books and periodicals will be most helpful? These are some of the questions which must be answered before daily planning can be effective. This section will analyze the requirements for daily planning in some detail. This analysis is followed by examples in which these elements are fused into a comprehensive daily plan.

Objectives

The necessity for formulating clear-cut objectives when designing meaningful classroom activities is obvious. The important point to remember is that the objectives should be so clearly stated that the activities originate in the objectives themselves. The objectives which are formulated for each lesson should be dependent on the teacher's evaluation of the previous day's lesson. For instance, let us look at the following objective: "To have children appreciate that the ocean is a home for many kinds of plants and animals." This is not a suitable objective, because it does not indicate the kinds of behavior or meaningful activities which will show this appreciation. Clearly this objective is not meaningful for use in daily planning. Compare the objectives on pp. 443–444; these are functional behavioral objectives, because they define the science work for the day. At the end of the class activities, the teacher is able to assess the progress which children have made in attaining the objectives.

The problem

In accordance with the philosophy of Inquiry, children will best achieve specific behavioral objectives when these objectives arise naturally in the course of problem solving. Such problems are often more or less general questions directed to a specific theme. Since the primary question may be too diffuse, it is usually subdivided into a series of questions whose scope is limited in order to expedite their study. With the knowledge gained by answering these subsidiary questions the learner is in a position to resolve the primary question. It is important that the questions of limited scope be anticipated by the teacher during the planning stages. The timing of these questions is difficult to determine, since it depends on the interaction of many variables. The question "Is the problem too difficult for the children and should it be made easier?" is frequently a stumbling block for teachers. Let us consider why. If the problem is excessively difficult, that is, beyond any hope of having a child successfully solve it, then the result is frustration and failure to learn. If the problem is too easy, it results in boredom and failure to learn. These are the extremes and do not present a significant problem even to most well-prepared beginning teachers. The difficult decision, which challenges even the most accomplished teacher, is to match the degree of problem difficulty with the learner's ability. The most effective basis for making this match is the teacher's intimate knowledge of the class. A general rule that may be employed is to make the problem a little more difficult, rather than a little easier, when there is doubt about the relationship of the problem difficulty to the learner's ability. It is relatively easy to simplify a difficult problem by asking more specific or leading questions. It is far more difficult to make a simple problem more challenging.

To properly match difficulty of the question to the ability of the learner requires clear thinking and intellectual honesty. The teacher must consider the nature of the subject and the abilities of the learners, and be flexible enough to continually modify the problem as experience indicates.

Rationale

Teachers often view statements of justification for specific daily lessons as unnecessary chores. When the justification is a restatement of the objectives in terms of purposes, then perhaps this opinion is well taken.

Statements of rationale should be made by teachers in order to establish definite ideas of why the lesson is being presented. It is not always necessary to *write* the justification or rationale, but it is imperative that careful consideration and thought be given to the reasons for presenting the lesson. Consider the statement, "It is the purpose of this lesson to have children gain an appreciation of the vast variety of plants and animals that live in the ocean." This statement, which does not differ from many statements of objectives, is empty and meaningless and serves primarily as a "lip-service" purpose. A valid problem design must be based on a valid rationale. Such a justification might be one in which the discovery of sea-water characteristics, as well as the relationship of plants and animals to these characteristics, is of prime importance. A lesson emerging from this justification could be based on the qualitative aspects of these factors. They would become the factors underlying the development of the lesson without being stated as objectives.

Many factors should be considered in establishing the justification of a lesson. Considerations of how important the lesson is to the learner, why a particular methodology should be avoided, and whether the substitution of one material for another is functional are all significant. The importance of making these justifications need not be overemphasized, especially for the experienced teacher, who in learning the art of teaching has learned to consider these factors intuitively if not automatically. For the beginning teacher, however, careful attention paid these factors will result in greater confidence in the planning process and will tend to insure success in execution of the lesson.

Methods

Specific methods for use in presenting ideas, concepts, and facts have previously been reviewed. The reader should be able to evaluate each of these methods for use in a given situation. The incorporation of specific methods is the easiest phase of preparing a lesson. The more difficult task that burdens teachers is determining the relationship between the individual learner on one hand and the subject matter and its mode of presentation on the other. How can a teacher ensure that all of the individuals in the class will actively participate in a planned activity? What factors must be considered when assessing the behavior of the bright student who is disinterested in the lesson? How can the slow learner be helped so that the lesson becomes both meaningful and achievable to him? It is the anticipation of these questions that is important in the planning process. Solutions to problems of this type are academic until the possible problem becomes a reality. In planning methods and techniques, the teacher must anticipate what might occur and so be ready to offer help when the need arises. Fortunately, the teacher has previous knowledge of the class on which to base estimates of what problems may arise and what solutions may be successful. Complete planning for these problems is impractical since time will not allow preparation for every eventuality. Hence, the teacher is called upon to be a performing artist in solving problems of methodology on the spot and in managing a situation with countless variables.

Motivation

Another consideration of planning, and one that is not unique to the Inquiry approach, is finding a center of interest around which to develop the major ideas of the daily lesson. The determination of a suitable interest center should be based on the past experiences of the learner. It should contain an element that is unknown, surprising, or in some way exciting to the child. The development of interest may be approached in any of a number of ways. The best known of these, and perhaps the easiest to execute, is the teacher demonstration. As an introductory technique, the well executed demonstration may include elements of surprise, unexpected or contradictory results, and other attention-getting devices. Techniques such as demonstrations are functional in building interest.

As effective as the demonstration, but by no means a substitute for it, and less difficult to execute because almost no equipment is necessary, is the use of a series of questions. Compared to techniques like the demonstration, questions are more difficult to plan, more dependent on the child's verbal ability, and more difficult to use successfully. In using questions to motivate a child's interest, the teacher must be careful to relate the questions to the main idea of the lesson in a way that will enable the child to work on the problems independently. The use of too many questions, or of questions which are broad or diffuse, tends to confuse the child when he goes to the laboratory to study a problem. Conversely, questions that are too limited in number or too direct in their approach do not challenge the child when he is studying a problem through firsthand experiences. If questioning is to serve a major motivational role, the teacher must exercise care in formulating each question, deciding when he has asked too few or too many questions, determining which questions have been effective with the learners and which should be modified or eliminated.

Let us examine several questions in an attempt to justify their use. "What factors affect the strength of an electromagnet?" as a single motivational question would be completely unacceptable for use with most fifth-grade children, even if the term "electromagnet" was known to the children. This question cannot be functional, because of its great breadth and its failure to give a hint of what specific factors might be studied. A child given just this question, or even several more like it, and a set of equipment to work with will be baffled as to how to start and what to do. If this question were to be used with more specific questions, there might result a more functional basis for learner activity. Suppose this question were to be coupled with the following:

1. How can the strength of a magnetic field be measured?
2. Does the number of wire turns around the bar have any affect?
3. What difference is there when bars of various metals are used?
4. Does the number of batteries make any difference?
5. Does the kind of wire used have any effect?

Each of these questions directs the child in some way. The first one suggests that before comparisons can be made a measurement technique must be developed. A measurement technique could present serious problems to the child. Additional help can be provided in the form of a diagram (see Figure 1) that is made available at the work table but is not explained.

Questions 2 to 5 all suggest specific ideas that the learner may wish to consider as the basis for experimentation. More questions could be asked, pertaining to the length of the wire used, the strength of the batteries, and other elements. The danger in asking all of the possible questions is that by doing so the child is deprived of a chance to develop ideas independently.

The use of questions as a basis for motivating children is at best a difficult technique, and successful learning appears to be directly related to how well the teacher is able to formulate and ask questions. The beginning teacher will find many questions difficult to ask and to assess, but with care and experience the task becomes manageable.

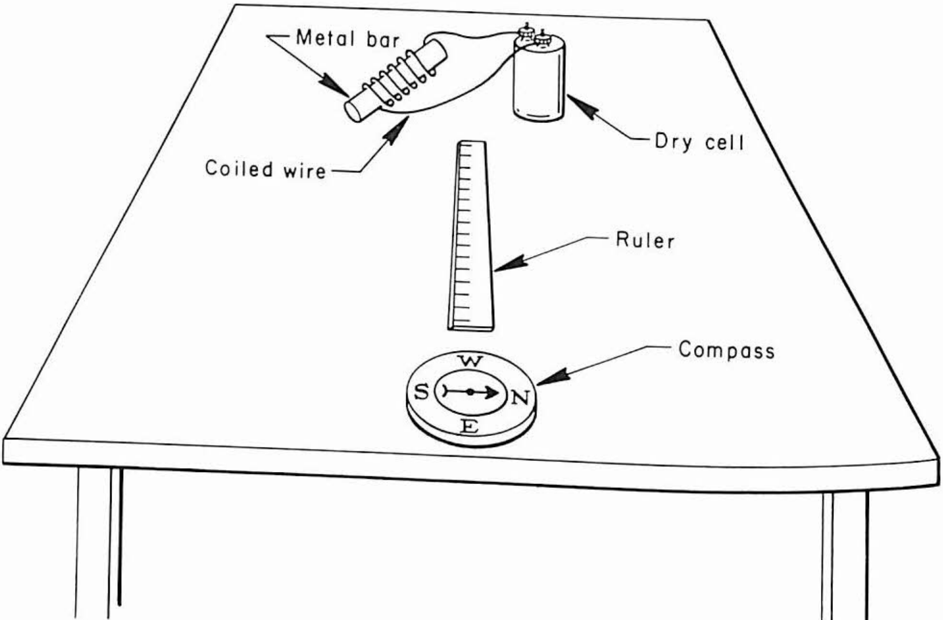

Figure 1

Materials

The tools of teaching have been discussed generally in previous chapters and will be further considered here in light of how they may be incorporated in a lesson. When planning an experiment, the teacher seeks materials which, when combined, will give the child as many avenues to understanding as he can effectively use. The selection of materials is based on criteria that include the inherent value of the device (as in a film), the comprehensibility (as in a book), and the ease of obtaining the equipment (as in scientific instruments). Let us choose, for purposes of illustration, the criteria for selecting materials used in doing an experiment. If the teacher is contemplating the use of a given apparatus, consideration must be made of how the child will react *to it* and *with it*. Would it be advisable to use an oscilloscope with second- or third-grade classes? Can the fourth-grade child manipulate a balance well enough to obtain the desired degree of accuracy? Is it safe for the second grader to use a Bunsen burner? Are the plants for use in the experiment known to the child, and if not, does it matter? Would the child benefit if one apparatus were substituted for another? All of these questions and more must be answered in light of the teacher's knowledge of the child, the equipment, and the problem. Other questions concerning the flexibility of the classroom, time factors, and safety factors must all be related to selection of equipment and materials.

The activity

The design of a learning activity must take many elements into account. For example, on what basis is the child expected to find a pathway toward understanding the concept? This pathway is inherent in the concept, and it is incumbent upon the teacher to discover it, design the activity so that the pathway can be found, and, finally, guide children to its discovery.

It may have been this pathway, or line of reasoning, that was followed when the idea was originally conceived. Even if some other pathway was responsible for the initial formulation of the concept, it is through the use of a line of reasoning in an activity that the child is provided with an opportunity to invent or reinvent the idea. The teacher must think through the idea completely in order to be familiar with at least one line of reasoning which appears to be suitable for the student to use in going from his present knowledge to an understanding of the concept. By having explored the conceptual framework and scheme of a concept, the teacher is prepared to design an activity that reflects the important phases of that concept. The preparation of the activity is made easier when this process is followed. Although the activity may not be easier to design, it will be conceptually sound.

The teacher's responsibility when following this process is far greater than in the preparation usually referred to as "keeping one chapter ahead." The factual information needed by the teacher is of no less importance here than in any other approach. The significant difference is found in the integration of the facts with each other and the development of a line of reasoning. The activity that emerges from preparations of this kind and the accompanying contemplations has a far greater chance for success than one that is prepared on some less valid foundation.

This discussion implies that the particular rationale underlying a concept is the basis on which an activity should be built. When designing the activity, the stepwise procedures that a child may find or follow must be inherent in the questions the teacher asks, the materials he provides, and the guidance techniques he uses. Any activity that meets these criteria has a good chance for success. However, it is clear that such instructions are more easily given than followed, and many errors should be expected before a successful activity is finally evolved.

Evaluation

Historically, many classroom teachers have thought of evaluation in terms of the conglomeration of techniques used in establishing grades for students. These have usually been characterized by announced and surprise quizzes, examinations, student responses during recitation, and assessment of written homework and classwork. In using an Inquiry approach to teaching science, evaluation of this kind is inadequate both in determining students' grades and, more important, in providing the teacher with the information needed for the teaching-learning process. The primary reason for the failure of traditional evaluation techniques to aid the teacher in the execution of a lesson is that the evaluation techniques are in large part employed *after the fact*. The procedure generally calls for the teacher's presenting the factual information and concepts and then applying evaluation techniques. The results of evaluation come too late to be helpful to the teacher in guiding the learning process. Evaluation that is concurrent with the teaching process is mandatory in the Inquiry technique since it enables the teacher to modify the lesson as it progresses. Suitable methods that provide immediate feedback during the lesson must be employed; the feedback information in turn is the basis for question formulation and other directive techniques used by the teacher in guiding the development of the learning process.

The forms of evaluation techniques are varied, and no one method can be chosen as the uncontestably best way to find out what and how children are learning. In many cases, an analysis of student reactions to the teacher-directed questions will provide the best insight into the child's understanding. Careful consideration of the questions asked by students also gives valuable clues. Other alternatives include observation of the child studying a problem, doing an experiment, or conversing with peers. The teacher must be constantly aware of the signs that indicate the degree of comprehension, interest, and involvement of the learner. In planning the lesson, the teacher must look for places to inject analyzing questions and to observe student reactions in other ways. Thus, when executing the lesson, the teacher will have a basis for adjusting the activities to yield the most effective learning outcomes.

Other factors

Complete and detailed daily lesson plans must include as many factors as are pertinent to the successful execution of the day's work. In order to consider all factors, the teacher would have to have far more time to plan than is practical. Compromising the completeness of plans depends on variations of subject matter, facilities, children, and teacher background, to name a few. The outcome of planning is the teacher's responsibility, and many problems need attention. Among the more important of these are: What special difficulties will children have with the vocabulary of the lesson? Are there communication barriers to be dealt with? How can the concept best be generalized? Is the method of summarizing meaningful? Should the idea be followed up with another lesson? What previously learned ideas can be incorporated?

All of these factors, when taken into account in proper perspective, will yield a more efficiently planned and more easily executed lesson.

Analysis of a sample lesson

To illustrate many of the previously discussed planning factors, let us inspect a pertinent lesson prepared by the AAAS. The selected lesson is aimed at developing the concept of predicting and is the third in a series. Only the pertinent parts of the lesson have been included.

Predicting 3: DESCRIBING THE MOTION OF A BOUNCING BALL

Objectives

At the end of this instruction, the children should be able to:

1. observe a ball dropping and state the height of the first bounce.
2. construct a bar graph showing the relationship of drop height of a ball to its bounce height.
3. state and apply the rule that the bounce height of a ball is directly related to the height from which it was dropped.

Rationale

In several activities in earlier exercises children have observed and described stationary or slowly moving objects.

This exercise will give the children further experience in using graphs to record and communicate experimental data...They will also use the graphs for prediction by interpolation between observed values... For *most children* it should be sufficient to use the pictorial relationship of drop to bounce height on the bar graphs. More *advanced children* may be introduced to ratios at this point even though a fuller treatment is not introduced until later in this program.

The observations on the bounce heights of balls of different kinds *may lead the children to ask* why different balls bounce differently. The explanations are complex and involve the elasticity both of the balls and of the surfaces on which they are bounced.

Materials

Balls (sponge rubber, golf, handball, tennis, ping-pong)—one of each kind for each group of three children.

Wrapping paper, *1.5 meters by 0.75 meters*—two pieces for each group of three children and two pieces for the teacher.

Originating the Problem

For this exercise it would be best if the class were arranged either in a semicircle or in some other manner so that every child would have a good view of the demonstrations being given.

1. The teacher drops (that is, releases without throwing) a sponge rubber ball, catches it as it bounces back, and asks the children to describe what they observed. Their discussion should include some description of the ball, its straight-line motion toward the floor and back, the blurry appearance of the ball while it is in motion, and the sound associated with bouncing.

2. The teacher drops the ball again but this time does not catch it. The children's description now should include the observation that at each successive bounce the ball goes up a shorter distance (height). The children may describe the height of the bounces in comparative terms; for example, a little higher than the table, as high as Johnny's chin. If the children do not think of counting the bounces, the teacher should ask: How many times did it bounce? The children should be able to count five or six bounces before the bounces get too close together to be counted.

Instructional Procedure

Activity 1

Fasten a sheet of wrapping paper to the wall with masking tape. The paper should extend from the floor to a height of 1.5 meters...Starting about 2 decimeters from the floor draw with black crayon six horizontal lines. The lines should be spaced...Put the zero line at...ask the children if the spaces...If there is any question about it ask a child to measure the space between...

In order to demonstrate the procedure to the other children for later small group activity, ask one child to hold the sponge rubber ball at the height of the 6-line and drop it without any throwing motion. The other children should count bounces, 1, 2, 3, 4, 5, 6, brrt.

A group discussion could be pursued here about such things as . . . Ask: How high did the ball . . . Ask the children to describe . . .

Activity 2

For Activity 2 the children should, if feasible, be arranged into groups of three. If the teacher prefers, or the facilities are not available for small group activity, this exercise could be taught as a whole group demonstration. A reasonable area of wall space is required. The floor at the base of the wall should be level and hard.

Before beginning the activity, the teacher should suggest that they note carefully the manner in which the ball bounces and any variation in the bouncing of the balls.

Encourage discussion in the groups like that suggested at the end of Activity 1.

Activity 3

Next tell the children that you would like them to mark on the chart how high the balls bounced. To do this they will need a way of showing the bounce height temporarily. Ask how they could do this. They could suggest that this could be accomplished by . . .

Generalizing Experience

Show the children a ping-pong ball to which a length of thread (about a meter long) has been attached by means of a small piece of masking tape. Suspending the ball by the end of the supporting thread, ask them to suggest a way this ball can be made to bounce sideways instead of up and down.

. . . Make a bar graph of the data. Ask the children to use the graph to predict the rebound height from a release position not tried previously. Ask them to test their prediction. If the children are sufficiently interested, the teacher might ask them to . . . They could plot these measurements as bar graphs and compare the graphs with those they made previously.

Appraisal

The children should use wall charts with a different scale; for example, 1 to 10 instead of 1 to 6. They should drop tennis balls and ping-pong balls from various heights, describe the results orally, and make individual bar graphs.

If desired, have the children drop a golf ball and mark the bounce height. It will be best to start with a drop height of a little more than a meter. Next have them drop the ball from the first bounce height and find the new bounce height. Repeat, each time dropping the ball from the preceding bounce height. Have the children mark the bar graph and ask them to describe what happened.

Summary

The way in which curriculum guides are usually used seems to promote a certain rigidity in the teaching-learning process. Often, the formal lesson plans which evolve from these guides curtail still further the learner's freedom. The daily lesson plan and the curriculum guide are nothing more than *guidelines* for successful teaching. They are tools by which the teacher may organize and record his ideas (learning stimulators) or classroom activities. The full development of these ideas should be left for the actual classroom. Planning and preparing for the "artistic" interpretation of ideas requires extensive effort in two major areas.

First, there must be an appropriate philosophical view of science education. From this will come clear statements of behavioral objectives and a rationale for presenting a lesson. The second area of planning is more concrete and includes the formulation or selection of (1) specific problems and questions for directing a learner's attention; (2) motivational techniques; (3) specific methods and techniques for presenting materials; (4) materials suitable for developing ideas; (5) worthwhile activities; (6) evaluation techniques to assess the learning process.

Planning in these terms is a continuing task, whose importance should not be underestimated. The time spent in thinking through the problems of classroom instruction will help children learn far better than the time spent on detailed lesson plans drawn from unimaginative curriculum guides.

For further study

1. Criticize the assumption that curriculum guides arbitrarily select the specific information to be presented.

2. Propose and justify an alternative to the adoption of a single textbook for a year's study.

3. Formulate several behavioral objectives that might be applicable to a lesson you have taught or will teach.

4. Suggest cases in which behavioral objectives may not be desirable, and justify these suggestions.

5. Select at random a science curriculum guide and rewrite its objectives in behavioral language.

6. How does our knowledge of children's conceptual abilities at given ages fit in with the problems of long-range planning? What are some of the difficulties which would arise if long-range planning were always to be tempered by the children's conceptual ability?

7. Formulate some questions that might be used in conjunction with an experimental procedure for children. Estimate the reactions that children may have to these questions. Restructure the questions in a way that may eliminate undesired reactions.

8. Select a science lesson you have previously taught and give its rationale.

9. For a science lesson, think up a motivational "device" that does not require any material objects.

10. Suggest criteria for evaluating students' progress during the course of an experiment.

11. Analyze critically the planning in the sample lesson *Describing the Motion of a Bouncing Ball.*

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